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Functionalization Of Cyclopalladated Ligands Using Secondary Phosphines And Meta-Chloroperoxybenzoic Acid

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FUNCTIONALIZATION OF CYCLOPALLADATED LIGANDS USING SECONDARY PHOSPHINES AND *META*-CHLOROPEROXYBENZOIC ACID

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This dissertation, submitted by Jonathan Edmund Kukowski in partial fulfillment of the requirements for the degree of Doctor of Philosophy from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done, and is hereby approved.

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LIST OF ABBREVIATIONS

AcO	Acetate
Ad	1-Adamantyl
Ar	Aryl
bimy	1*H*-Benzimidazole
Bn	Benzyl
Bu	Butyl
Bz	Benzoyl
bzq^C	Cyclopalladated benzo[*h*]quinoline
m-CPBA	*meta*-Chloroperoxybenzoic acid
CPC	Cyclopalladated complex
Cy	Cyclohexyl
dba	Dibenzylideneacetone
DIPEA	*N*,*N*-Diisopropylethylamine
DKR	Dynamic kinetic resolution
DMSO	Dimethylsulfoxide
diphos	1,2-Bis(diphenylphosphino)propane
DMAP	4-Dimethylaminopyridine
DPPB	1,4-Bis(diphenylphosphino)butane
ee	Enantiomeric excess

Et	Ethyl
HMPA	Hexamethylphosphoric triamide
HPLC	High performance liquid chromatography
HRMS	High resolution mass spectrometry
L^C	Cyclopalladated ligand
Me	Methyl
MeCN	Acetonitrile
Mes	2,4,6-Trimethylphenyl
ND	Not determined
Nor	Norbornene
ONf	Nonafluorobutanesulfonate
ORTEP	Oak Ridge thermal ellipsoid plot
Ph	Phenyl
PhMe	Toluene
Pr	Propyl
TfO	Trifluoromethanesulfonate
TLC	Thin-layer chromatography
THF	Tetrahydrofuran
Tol	Tolyl

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ABSTRACT

Cyclopalladation of organic ligands followed by reactions at the C–Pd bond with MPR_2 (M = Li, K, or H) or other reagents (e.g. oxidants) is a desirable strategy for the synthesis of hemilabile bidentate ligands due to the large library of known cyclopalladated complexes (CPCs). This dissertation is composed of three projects on the functionalization of cyclopalladated ligands.

In the first study, a new method for sp^3C–P bond formation using diphenylphosphine was studied. Conditions for the synthesis of aminophosphines were optimized for the reactions of dinuclear chloro-bridged sp^3C–Pd CPCs and $HPPh_2$. The best yields were obtained with 9 equivalents of phosphine in CH_2Cl_2 in the presence of Cs_2CO_3 at 35 °C. The scope of the reaction was explored with a range of enantiopure and achiral *C,N* and *C,P* CPCs. The corresponding *N,P* and *P,P* ligands or their oxides were isolated in 30–65% yields. Reactions of $HPPh_2$ in toluene with CPCs derived from D-camphor methyloxime and 2-*tert*-butyl-4,4-dimethyl-2-oxazoline provided unique mononuclear Pd(II) complexes with a terminal PPh_2 ligand in 16 and 52% yield, respectively.

The electronic and steric effect of secondary phosphines were studied in phosphination reactions of cyclopalladated ligands. HPR_2 with electron-donating and -withdrawing aryl groups (R = *p*-$MeOC_6H_4$ or *p*-$CF_3C_6H_4$), bulky groups (R = mesityl or 1-adamantyl) and non-equavalent substituents (R^1 = *t*-Bu, R^2 = Ph) were reacted with CPCs

derived from *N,N*-dimethylbenzylamine and enantiopure L-fenchone methyloxime, 1-(*N,N*-dimethylamino)ethylphenyl, and di-2,4-*tert*-butyl-2-oxazoline. With large molar ratios of phosphine to CPC (9:1 or 4.5:1), C–PR_2 bond formation occurred to produce the corresponding aminophosphines or phosphine oxides in 56–61% and 12–44% yields, respectively. For both sp^2C–Pd and sp^3C–Pd CPCs, the reaction was tolerant to electronic differences in the phosphine substituents, but the sterically hindered phosphines dimesitylphosphine and HP*t*-BuPh reacted only with the fenchone-derived CPC to give the *N,P* ligand products in 32 and 12% yield, respectively.

Finally, an approach to the synthesis of *N,O* ligands was studied via the oxygenation of (*S*)-4-*tert*-butyl- and (*S*)-4-ethyl-2-phenyl-2-oxazoline CPCs with *meta*-chloroperoxybenzoic acid (*m*-CPBA). Reactions were performed at room temperature in methylene chloride, ethyl acetate, or acetonitrile followed by workup with lithium chloride. Oxidation products formed in these reactions included dinuclear complexes (*S,S*)-di-μ-Cl(κ^2-*N,O*)$_2$Pd$_2$, (*S,S*)-di-μ-oxo(κ^2-*N,O*)$_2$Pd$_2$Cl$_2$, and (*S,S*)-di-μ-(*m*-Cl-$C_6H_4CO_2$)(κ^2-*N,O*)$_2$Pd$_2$, as well as mononuclear derivatives (*S,S*)-bis(κ^2-*N,O*)Pd and dinuclear monooxidation complexes (*S,S*)-di-μ-Cl(κ^2-*N,O*)(κ^2-*C,N*)Pd$_2$. Each complex was isolated in low yield (6−46%) with the combined yield of oxidation products reaching up to 64%. The best selectivity in product distribution was observed for the reactions of μ-OAc-CPCs with 2.7 equivalents of *m*-CPBA in acetonitrile.

All new compounds were characterized by 1H, 13C{1H}, and 31P{1H} NMR spectrometry, and their purity was proven by satisfactory elemental analysis. X-ray crystallographic data were obtained for a new cyclopalladated complex derived from *O*-methyloxime L-fenchone having HP(mesityl)$_2$ as an ancillary ligand.

CHAPTER I

INTRODUCTION: ADVANCEMENTS IN C–PR2 (R = ALKYL OR ARYL) BOND FORMATION REACTIONS INVOLVING PALLADIUM

I.1. Background

Tertiary phosphines have an important role in modern organic synthesis, primarily as ligands for transition-metal catalyzed reactions including C–C,[1] C–N,[2] C–O,[3] and C–F[4] couplings and other transformations.[5, 6] They are also used as organocatalysts,[5, 7-9] as components of electronic materials,[10, 11] and in coordination chemistry of platinum,[12] iron,[13] and other metals.[14, 15]

The library of known phosphines is entirely synthetic, though a variety of C–P bond-containing compounds such as phosphonic acids, $P(=O)(OH)_2R$,[16] as well as a single example of a phosphinic acid, $P(=O)(OH)R^1R^2$,[17] have been isolated from biological sources. The diversity of reported phosphines has grown considerably over the last two decades to include structures with unique combinations of denticity, electron density, bulkiness, and chirality to suit the needs of their many applications. Methods for their preparation have also multiplied in recent years. Conventional approaches to tertiary phosphines via $C–PR_2$ (R = alkyl or aryl) bond formation can be divided into three categories: 1) the reaction of chlorophosphines ($ClPR_2$) with organometallic reagents, especially organolithium ones, 2) nucleophilic substitutions, including ring-opening reactions, with alkali phosphides (MPR_2), and 3) palladium-catalyzed hydrophosphination of unsaturated compounds.[18] These and other less common methods often rely on

organocatalysts or non-palladium transition metal catalysts,[19, 20] but transformations involving Pd have been the most prolific due to the versatility of Pd-mediated C–H activation.

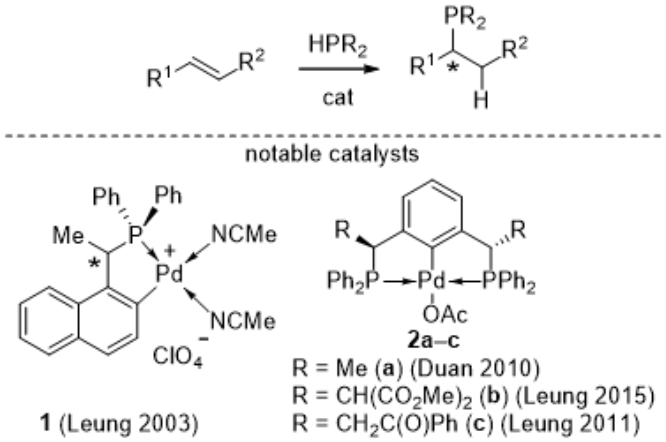
It is the aim of this introduction to discuss the latest studies (from 2012) in C–PR_2 (R = alkyl or aryl group) bond formation involving P(III) compounds and Pd(0) or Pd(II) species as either reagent or catalyst. It has to be mentioned that the end products of many reactions summarized in this chapter are often not tertiary phosphines, but their more stable derivatives such as oxides, sulfides, or boranes formed after appropriate treatment of PR_3.

I.2. Hydrophosphination Reactions

I.2.1. Background

Palladium-catalyzed asymmetric addition of secondary phosphines to unsaturated compounds (i.e., activated alkenes and alkynes) was described at length in 2016 reviews by Pullarkat[21] and by Chew and Leung.[22] I will here discuss only the subsequent publications, aside from a brief introduction to the topic, since direct methods for the catalytic and asymmetric introduction of the PR_2 moiety are highly desirable.

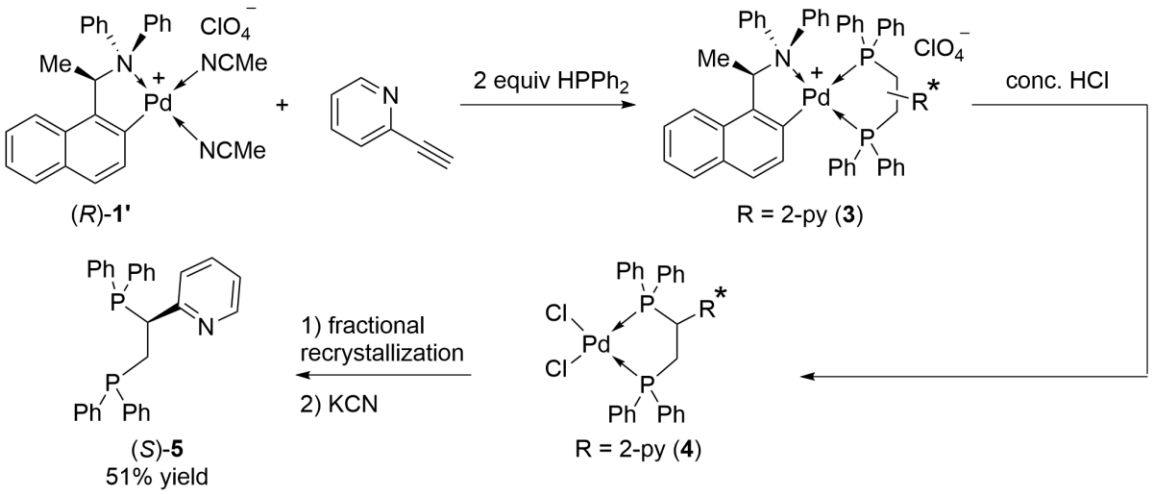
The groups of Leung and Duan have been instrumental in the field of Pd-catalyzed hydrophosphination since its re-emergence in 2010.[21] Reports have covered additions to a wide variety of electron-deficient trans alkenes (Scheme 1), mostly *α,β*-unsaturated carbonyl compounds, but the methodology has also been extended to nitroalkenes,[23] ketimines,[24] alkynes,[25] *α,β,γ,δ*-unsaturated sulfonic[26] and bisphosphonate esters,[27] as well as heterocycle-conjugated alkenes.[28] These transformations have been catalyzed by two principle types of palladium complex, enantiopure phosphapalladacycles (*S*)- and (*R*)-**1**[29] and the *P,C,P* pincer complexes (*S,S*)-**2a–c**.[30-32]



Scheme 1. Asymmetric hydrophosphination of electron-deficient alkenes by (*S*)-**1**, (*R*)-**1** and (*S*,*S*)-**2a–c**.[29-32]

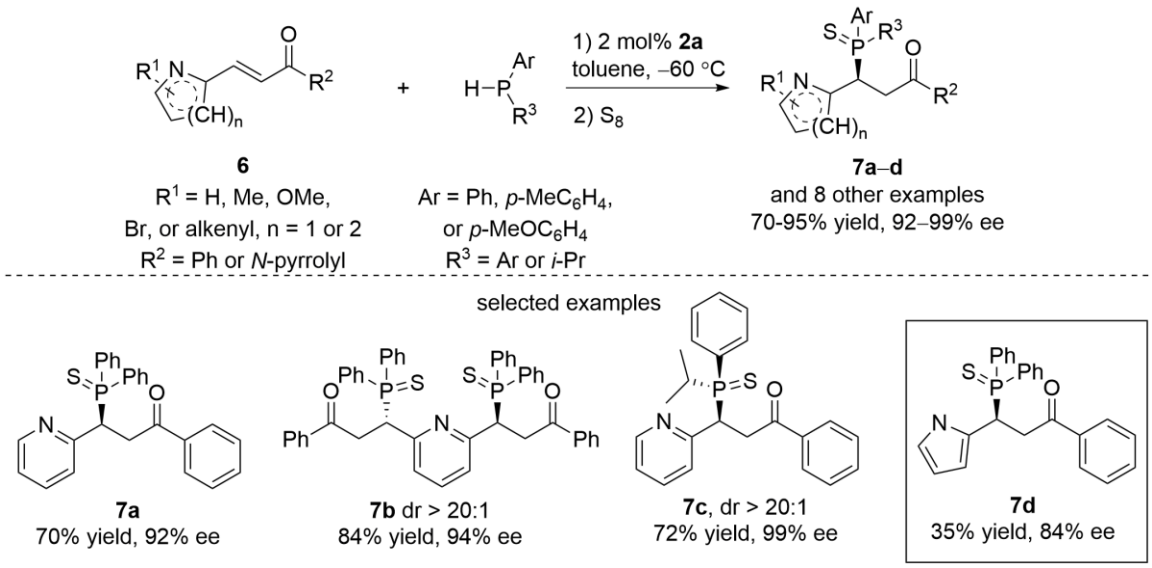
I.2.2. Recent Developments

One of the challenges associated with catalytic hydrophosphination has been the synthesis of aminophosphines and diphosphines. Chelation of these products to Pd can result in catalyst poisoning, particularly for non-pincer complexes such as **1** containing two monodentate ligands.[33-35] However, these transformations can be achieved with stoichiometric amounts of palladium. Yao and coworkers have recently reported the synthesis of a PROPHOS-type [1,2-bis(diphenylphosphino)propane] ligand via asymmetric diphosphination of 2-ethynylpyridine using equimolar amounts of the nitrogen analog of palladacycle (*R*)-**1** as an enantiopure template (Scheme 2).[36] After the addition of two equivalents of $HPPh_2$, four diastereomers of complex **3** were obtained. The enantiopure diphosphine (*S*)-**5** was recovered after mixing compound **3** with conc. HCl followed by fractional recrystallization of complex **4** and ligand liberation with KCN.



Scheme 2. Synthesis of PROPHOS-type diphosphine (*S*)-**5** by asymmetric hydrophosphination.[36]

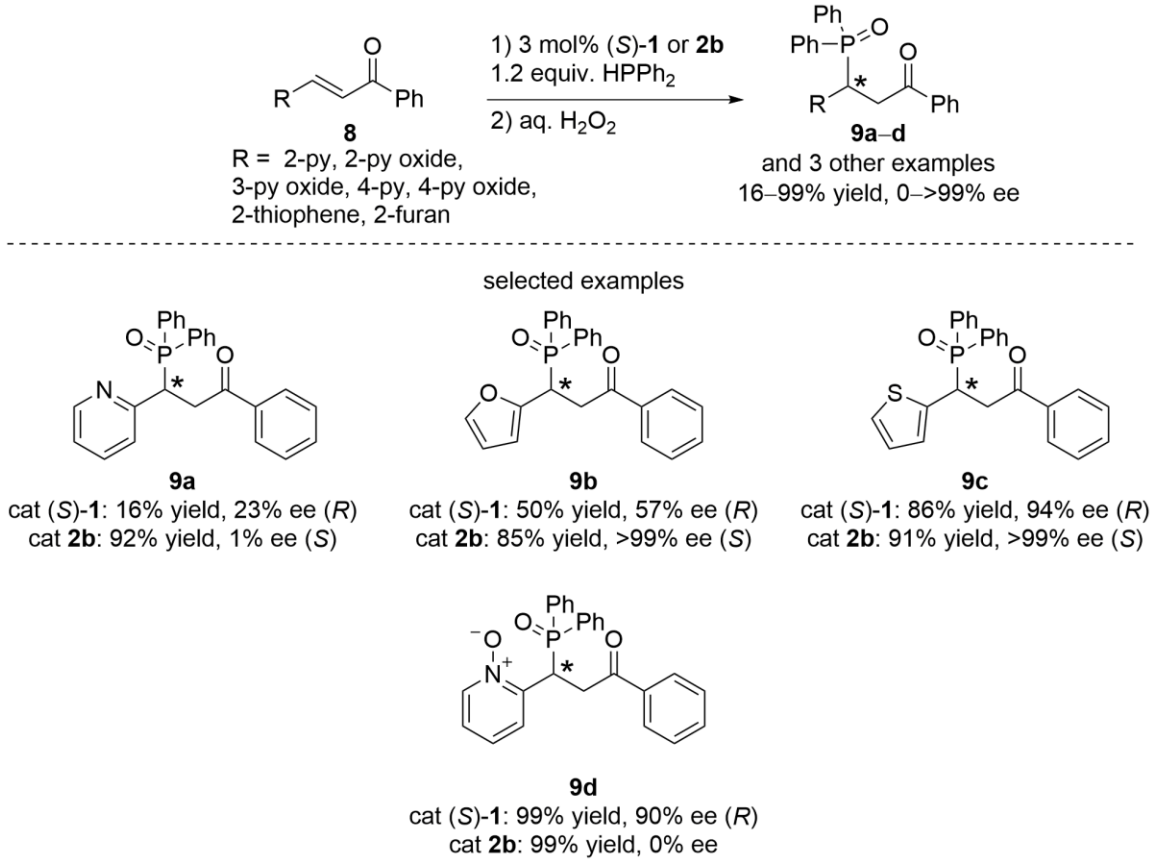
Song and coworkers have recently reported an alternative solution to the problem of catalyst inhibition in the preparation of *P,P*, *N,P*, and related ligands. Specifically, they proposed using the robust pincer complex (*S,S*)-**2a**.[37] HPR_2 was reacted with enones **6** containing the 2-pyridinyl ring. The catalyst showed high efficiency at room temperature (rt) providing desirable products in high yields and high enantiopurity, which were improved further in experiments conducted at lower temperatures. The addition was tolerant to a variety of substituents in the 3- and 6-pyridinyl positions, including Me, Br, and MeO (Scheme 3). As a unique example, a bis(enone) was used in the synthesis of an achiral *N,P,N* ligand (**7b**) in high yield. The phosphine reactants were varied to give *N,P* ligands with different PAr_2 substituents (where Ar = Ph, *p*-MeC_6H_4, or *p*-$MeOC_6H_4$) as well as compound **7c** with the P*i*-PrPh group. The authors also described the synthesis of the 2-pyrrolyl *N*-donor ligand **7d** from the corresponding enone.



Scheme 3. Enantioselective synthesis of *N*,*P* chelating ligands **7a–d** using catalyst (*S*,*S*)-**2a**.[37]

Pincer complexes may be better suited as catalysts for hydrophosphination reactions in which the products are *N*,*P* ligands, since they have only one site for coordination and, therefore, little chance of poisoning via product chelation. Yang and coworkers have recently compared two types of complexes, (*S*)-**1** and (*S*,*S*)-**2b**, in hydrophosphination of enones to assess the impact of different heteroatoms (*N*, *O*, and *S*) in various positions (Scheme 4).[38] In these reactions, catalyst (*S*)-**1** gave the products in good yields and high enantiopurity with few exceptions. Yields and enantiomeric excesses (ee) of products **9a–c** were in the order of 2-pyridinyl (16% yield, 23% ee) < 2-furyl (50% yield, 57% ee) < 2-thienyl (86% yield, 94% ee) according to the dipole moment of the chelating *N*, *O*, and *S* atoms. In general, $HPPh_2$ additions using the pincer complex gave *R*-chiral phosphines with excellent enantiopurity. Interestingly, although yields were high in all cases, enantioselectivity was negligible in reactions of enones with 2-pyridinyl (**9a**) and 2-pyridinyl-oxide (**9d**) substituents. However, as mentioned above, Song reported 92% ee

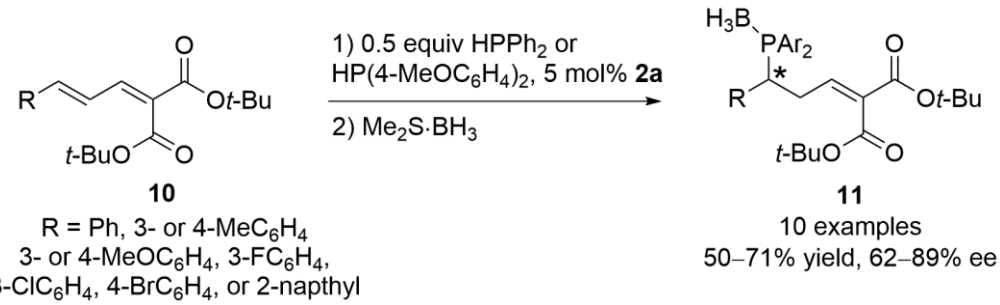
for the same 2-pyridinyl-substituted enone and a similar catalyst, albeit under modified conditions (1.2 equivalents of enone to $HPPh_2$ at –60 °C in toluene[37] *vs.* 1.2 equivalents of $HPPh_2$ to enone at –25 °C in acetone). The article confirmed that while the application of catalyst (*S*)-**1** is limited in the preparation of *N,P* ligands and suitable in the synthesis of *O,P* and *S,P* ligands, pincer complex **2b** maintains high catalytic activity for obtaining all three groups of bidentate compounds, although stereocontrol is lost in some cases possibly due to the reaction conditions or modifications on the catalyst pendant arms.



Scheme 4. Catalytic hydrophosphination of enones **8** using catalysts (*S*)-**1** and (*S,S*)-**2b**.[38]

Building on the work reported by Leung's group in which a pincer complex catalyzed the 1,6-addition of $HPPh_2$ to *α,β,γ,δ*-unsaturated malonic esters (**10**),[26] Wei and coworkers investigated the factors affecting stereoselectivity of this transformation.[39] The

bulk of the ester group was first varied, showing a trend towards 1,6- over 1,4-addition with increasing size. When isopropyl or *tert*-butyl substituents were installed in the ester moiety, a 15:1 ratio of 1,6-addition product to 1,4-addition was observed, whereas the ratio decreased to 9:1 and 1:1, respectively, for ethyl and methyl groups. The bulk of the alkoxy moiety was also positively associated with enantioselectivity (38% ee for methyl *vs.* 89% for *tert*-butyl), whereas the choice of solvent had no effect, nor was it found to affect the regioselectivity of the reaction. The transformation was found to be effective for a range of 2-substituted *tert*-butyl malonic ester derivatives with conjugated aryl groups containing electron-withdrawing and -donating substituents (Scheme 5).



Scheme 5. Catalytic 1,6-addition of $HPAr_2$ to *α,β,γ,δ*-unsaturated malonic esters **10**.[39]

I.2.3. Catalyst Design

Palladacycle **1** has been established as an excellent catalyst in asymmetric hydrophosphination reactions, but a significant drawback is its tedious multistep synthesis.[29] Based on earlier studies regarding interactions with H^8 of the naphthyl group and the substituent at the pseudobenzylic position (Figure 1),[40] Li and coworkers theorized that increasing the steric bulk of the chiral moiety may impart greater stereocontrol in catalytic reactions.[41]

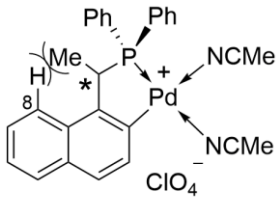


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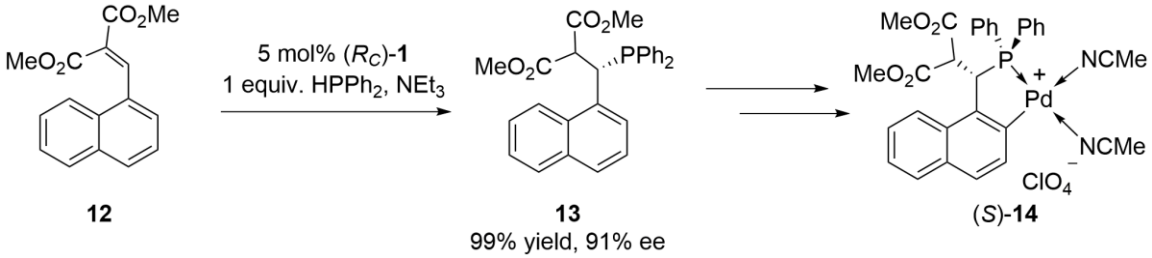
Figure 1. Important steric interactions in complex **1**.[40]

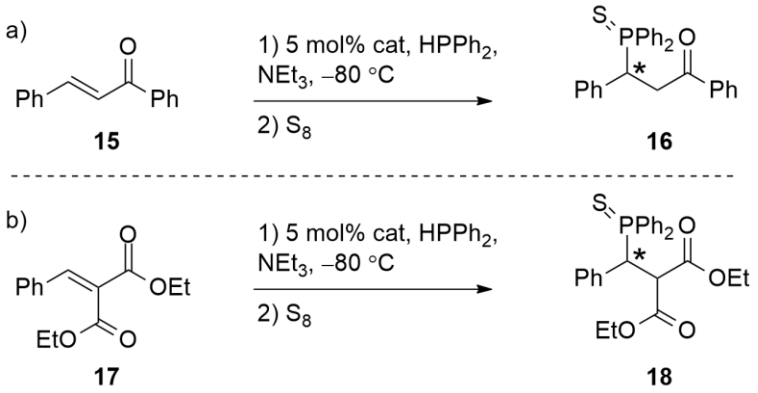
This group employed CPC (*R*)-**1** in the catalytic hydrophosphination of naphthyl-substituted alkene **12** (Scheme 6). Phosphine **13** was then cyclopalladated, and the Pd(II) complex [(*S*)-**14**] formed was tested for catalytic activity in the asymmetric hydrophosphination of chalcone (**15**) and *α,β*-unsubstituted malonic ester **17** (Scheme 7). Although the selectivity in both reactions was lesser (78% ee and 84% ee) than that observed with complex (*R*)-**1** (89% ee and 95% ee; see Table 1), the results are still promising given the synthetic ease and versatility of this approach to catalyst synthesis.



12 **13** (*S*)-**14**

99% yield, 91% ee

Scheme 6. Preparation of catalyst (*S*)-**14.**[41]

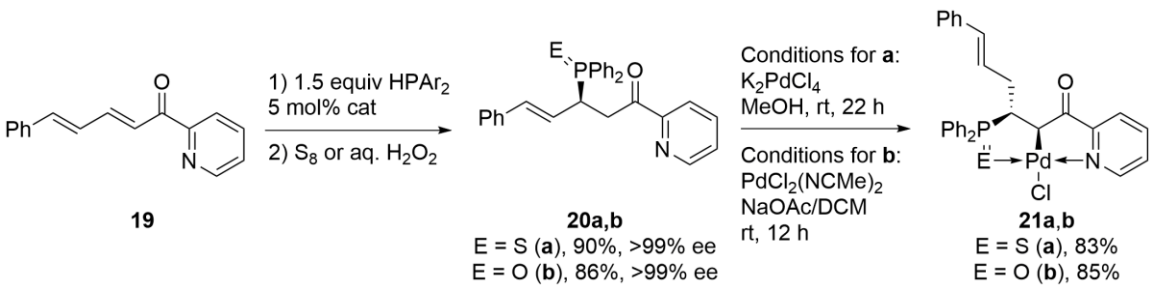


Scheme 7a,b. Asymmetric hydrophosphination of a) chalcone **15** and b) malonic ester **17**.[41]

Table 1. Data for the reactions shown in Scheme 7.

Entry	Cat.	t (h)	Product	Conv. (%)	ee (%)
1	(*R*)-**1**	6	**16**	99	89 (*S*)
2	(*S*)-**14**	6	**16**	99	78 (*R*)
3	(*R*)-**1**	96	**18**	99	95 (*S*)
4	(*S*)-**14**	96	**18**	99	84 (*R*)

Complexes with an sp^3C–M (M = transition metal) bond are expected to hold higher electron density on the metal center and as a result may show greater reactivity in some transformations.[42] In two recent reports from Leung's group, the synthesis of new pincer complexes with an sp^3C–Pd bond was undertaken via hydrophosphination of enones followed by cyclopalladation (Scheme 8). A 1,4-addition of $HPPh_2$ to enone **19** followed by chalcogenation and cyclopalladation offered the "self-breeding" catalysts **20a,b** (Table 2).[43] Catalyst **21a** furnished the preligand from its own structure with similar efficiency to catalyst (*S*)-**2b** in the catalytic hydrophosphination of **19**; its unsymmetrical and aliphatic scaffold could also be useful for more sterically demanding reactions.[42]

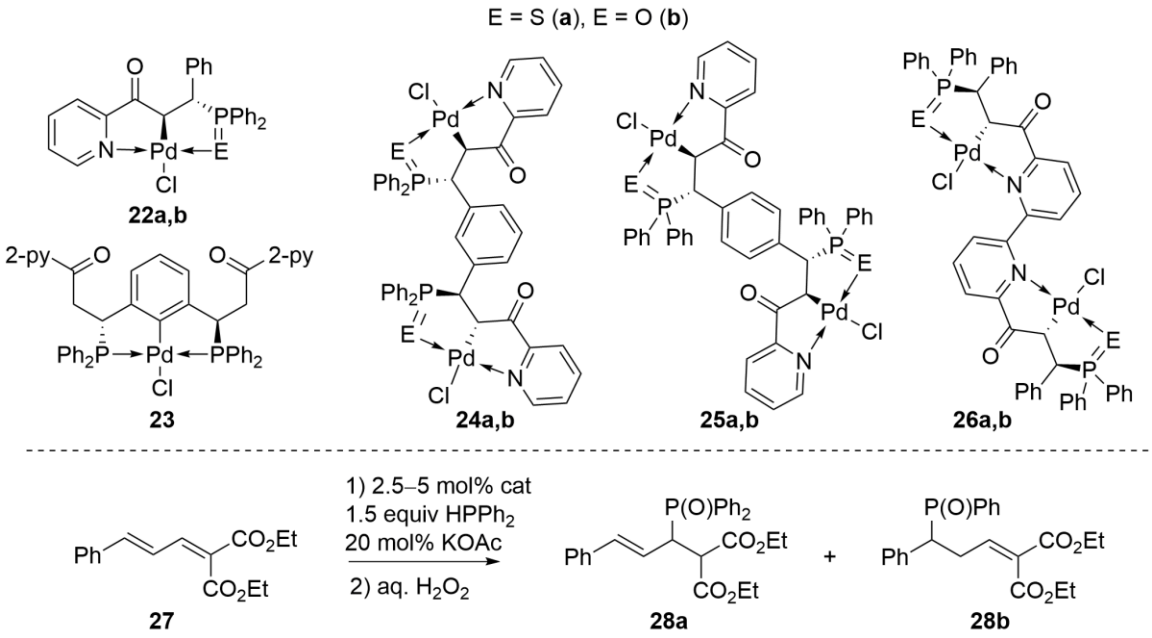


Scheme 8. Synthesis of catalysts **21a**,**b**.[43]

Table 2. Asymmetric hydrophosphination of **19** using pincer catalysts (*S*)-**2b** and **21a,b**.

Entry	Cat.	Base	t (h)	Solvent	T (°C)	Product	Yield (%)	ee (%)
1	**2b**	None	6	acetone	0	**20a**	90	>99
2	**2b**	None	6	acetone	0	**20b**	86	>99
3	**21a**	KOAc	24	thf/H_2O	Rt	**20a**	82	96
4	**21a**	KOAc	24	thf/H_2O	Rt	**20b**	85	93
5	**21b**	KOAc	24	thf/H_2O	Rt	**20a**	69	46
6	**21b**	KOAc	24	thf/H_2O	Rt	**20b**	66	45

Tay and coworkers applied the same methodology to synthesize preligands to catalysts **22–26** (Scheme 9).[44] Mononuclear (**22a,b** and **23**) and dinuclear (**24–26a,b**) complexes were obtained and tested for their activity alongside CPC (*S*)-**1** in reactions of *α,β,γ,δ*-unsaturated malonic ester **27**. The results are summarized in Table 3. The sp^2C–Pd pincer complex **23** outperformed all other sp^3C–Pd complexes, while the latter group showed only low catalytic activity and chirality induction.



Scheme 9. $HPPh_2$ addition to the conjugated diene **27** catalyzed by complexes **22**–**26**.[44]

Table 3. Results of the reactions shown in Scheme 9.

Entry	Cat.	**28a**:**28b**	Yield (%)	ee (%)	Entry	Cat.	**28a**:**28b**	Yield (%)	ee (%)
1	**22a**	1.3:1	23	ND*	6	**25a**	0:100	28	ND
2	**22b**	1:6	38	<10	7	**25b**	1:5.3	36	ND
3	**23**	1:13	69	40	8	**26a**	1:1.7	43	ND
4	**24a**	1:11.9	64	ND	9	**26b**	1:4.3	49	ND
5	**24b**	1:11.9	57	ND	10[45]	(*S*)-**1**	0:100	100	>99 (*S*)

*Not determined

I.3. Stereoconvergent C–P Bond Formation

I.3.1. Background

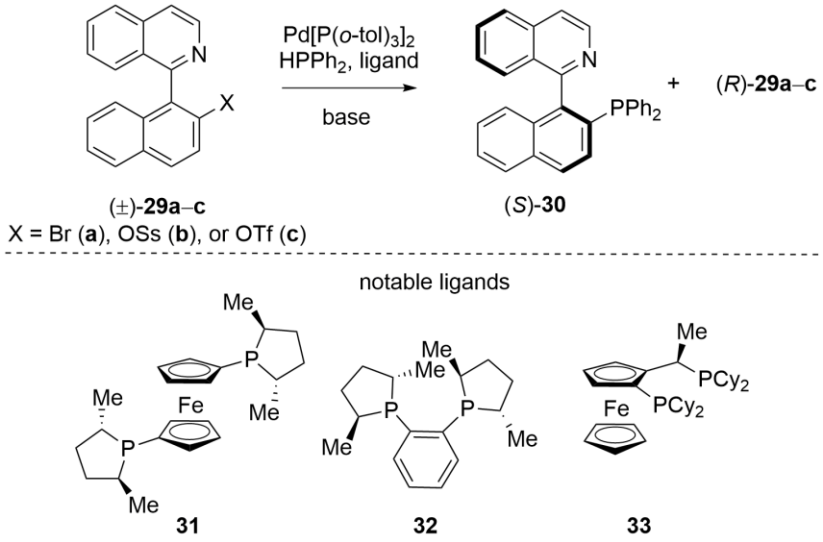
Strategies for the direct synthesis of enantiopure phosphines are highly valuable as they allow researchers to bypass the often laborious process of chiral resolution or the use of chiral auxiliaries in stoichiometric amounts. Enantioselective introduction of the PR_2 group using optically active catalysts to create a new chiral center is the most common approach to avoid chiral resolution and has been broadly used in hydrophosphination

reactions (*vide supra*). Another group of asymmetric transformations includes stereoconvergent processes, in which both enantiomers of a racemic reactant provide a stereochemically identical product. One such method is dynamic kinetic resolution (DKR), which relies on the fast isomerization of a reactant or intermediate followed by preferential reaction of one stereoisomer over the other.[45]

I.3.2. Dynamic Kinetic Resolution for the Synthesis of Axially Chiral Aminophosphines

A DKR approach has recently been reported for the asymmetric synthesis of 1-(2-(diphenylphosphino)naphthalen-1-yl)isoquinoline (QUINAP) by Bhat and coworkers.[46] Commercially available enantiopure *P*,*P* ligands were evaluated in the catalytic phosphination of racemic precursors **29a–c** using $HPPh_2$ (Scheme 10). In the case of bromide (±)-**29a**, dialkylphosphino ligands were found to exert greater stereocontrol than diarylphosphino analogs and were effective at slightly lower temperatures (80–90 °C compared to 100 °C). (*S*)-QUINAP (**30**) was obtained from (±)-**29a** in high ee using $Pd[P(o\text{-tol})_3]_2$ with either (*S*,*S*)-Me-Ferrocelane (**31**) or (*S*,*S*)-Me-DuPhos (**32**) as enantiopure ligands (Table 4, entries 1 and 2). The same transformations also provided the *R* isomer of bromide **29a**, which was then converted to (*R*)-QUINAP in separate experiments. Gram-scale reactions involving $HPAr_2$ were also performed at low catalyst loadings with tetra-*n*-butyl ammonium bisulfate as an additive (entries 3 and 4; $HPAr_2$ with the highest yields are listed). The DKR approach was not investigated further for bromide (±)-**29a**, since kinetic measurements revealed that the product racemized much faster ($t^{rac}_{½}$ = 0.5 h at 150 °C) than the starting reactant ($t^{rac}_{½}$ = 78 h at 150 °C). Although the sosylate (OSs, methanesulfonylbenzenesulfonate) derivative **29b** showed a favorable racemization

rate ($t^{rac}_{½}$ = 17 h at 90 °C compared to 246 h for QUINAP at the same temperature), DKR reactions provided low yields (entries 5 and 6).



Scheme 10. Asymmetric synthesis of QUINAP (*S*)-**30** from racemates **29a–c**.[46]

Table 4. Results for the reaction depicted in Scheme 10.

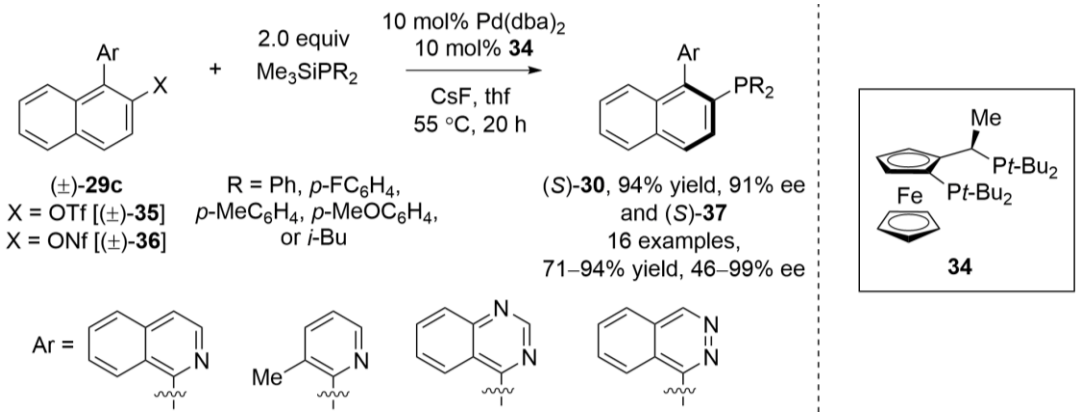
Entry	cat mol%	(±)-**29**	Lig.	t (h)	Base/ Additive	(*S*)-**30** Yield/ee (%)	(*R*)-**29a–c** Recovery/ee (%)
1	5	**a**	**31**	12–24	DIPEA	47*/84	47*/>96
2	5	**a**	**32**	12–24	DIPEA	43*/90	43*/88
3	0.5	**a**	**31**	20	DIPEA/ *n*-Bu_4NHSO_4	45/95	47/96
4[†]	0.5	**a**	**31**	14	DIPEA/ *n*-Bu_4NHSO_4	46/92	44/96
5	2	**b**	**31**	8	DMAP	39/82	41/96
6	8	**b**	**31**	96	DMAP	43/56	ND[§]
7	5	**c**	**31**	15	DMAP	100*/0	ND
8	5	**c**	**33**	6	DMAP	86/90	ND

*Conversion of starting material measured by UHPLC-MS.
[†]$HP(p\text{-tol})_2$ was used instead of $HPPh_2$.
[§]ND = not determined.

To improve yields, the authors described reactions involving triflate (±)-**29c**. In this case ligand **31** (entry 7) and bulkier variants, although highly active, provided only racemic

QUINAP. After re-evaluation of commercially available diphosphines and optimization of conditions, (*S*)-QUINAP was obtained in 90% ee with the (R,S_{Fc})-Josiphos ligand **33** (entry 8). Interestingly, the rate of reaction between compound (±)-**29c** and $HPPh_2$ in the presence of $Pd[P(o\text{-tol})_3]_2$/**33** at 80 °C is several orders of magnitude greater than the racemization rate of the triflate, suggesting that in this case DKR is dependent on the isomerization of Pd complex intermediates. When a longer time was allowed for this process, as by slow addition of $HPPh_2$ over several hours, the enantioselectivity was found to be the greatest.

Ramírez-López and coworkers reported a similar DKR method for the asymmetric synthesis of axially chiral *N,P* ligands including QUINAP.[47] Their approach employed trimethylsilylphosphines (Me_3SiPR_2) rather than secondary phosphines or metal phosphides in the reaction of heterobiaryl triflates and nonaflates (Scheme 11). As in the study by Bhat and coworkers[46] planar chiral Josiphos ligands proved to be the most effective, with ligand **34** chosen for the model reaction. In addition to **29c**, triflate and nonaflate compounds containing 3-methylpyridine, quinazoline, and phthalazine moieties were also used, and several phosphines were tested to assess the impact of electron-donating and -withdrawing groups. The reaction was found to be tolerant to these variations in the starting compounds and provided phosphines (*S*)-**30** and (*S*)-**37** in good yields and with high ee in most cases. DFT calculations undertaken by the group supported several conclusions regarding the mechanism. Namely, the cyclopalladated complex **38** formed by displacement of the triflate group in the starting substrate **29c** by Pd(0) was shown to be prone to epimerization (Figure 2). The less stable *S* isomer of complex **38** is more likely to proceed to a reaction intermediate, which undergoes the irreversible reductive elimination step to produce phosphine (*S*)-**30**.



Scheme 11. Asymmetric DKR synthesis of axially chiral *N*,*P* ligands.[47]

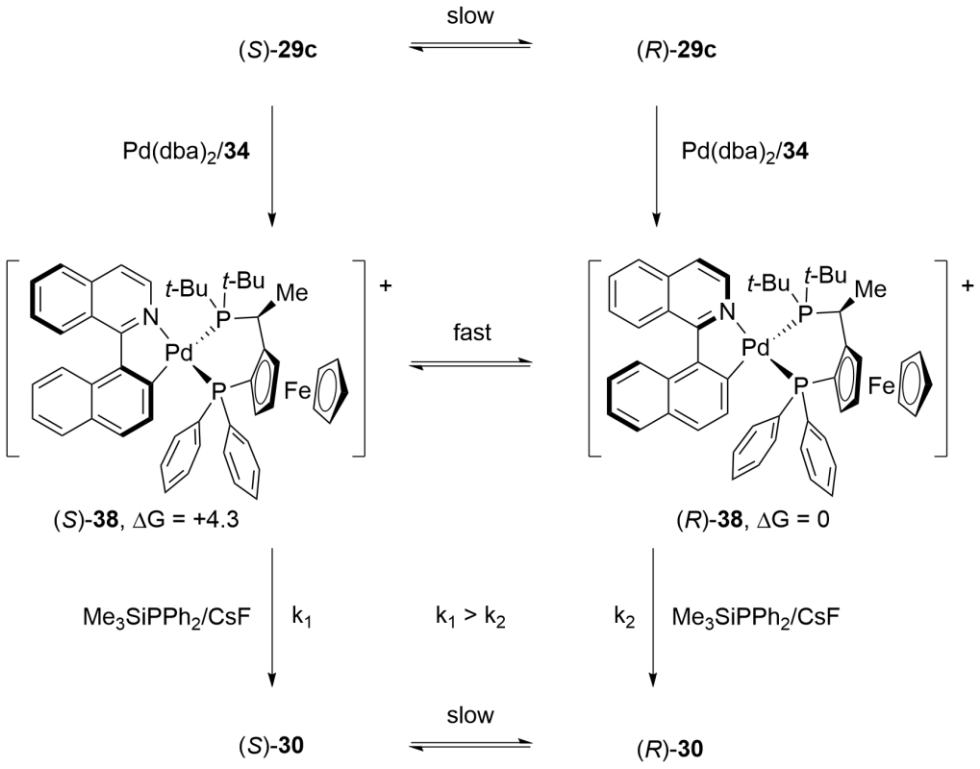
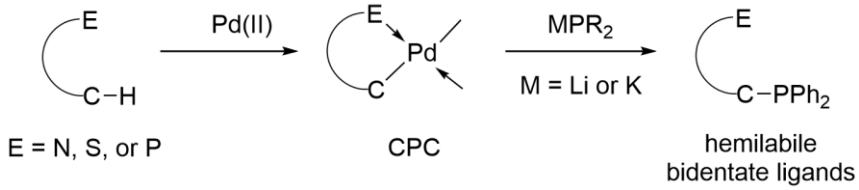


Figure 2. Simplified reaction pathway of C–P bond formation from heterobiaryl compounds and Me_3SiPR_2 reported by Ramírez-López and coworkers.[47]

I.4. Reaction of Cyclopalladated Complexes

I.4.1 Background

Cyclopalladated complexes, or CPCs, have been used extensively as reactants in various regioselective ligand modification reactions.[48] Recently, a two-step approach consisting of 1) cyclopalladation of appropriate preligands followed by 2) substitution of the metal in the C–Pd bond by a PR_2 group (Scheme 12) became an alternative to the traditional methods of C–PR_2 bond formation involving lithiation or halogenation and subsequent reaction with chlorophosphines or metal phosphides, respectively. These conventional approaches to phosphination require the initial introduction of either a lithium or halogen moiety; however, this is not always straightforward, especially with regard to functionalizing alkyl fragments. The use of CPCs as reactants in phosphination provides access to a wide variety of hemilabile bidentate ligands, with a phosphino group and additional functional group in the structure, due to the wealth of known palladacycles with an sp^3C–Pd and sp^2C–Pd bond.[49]

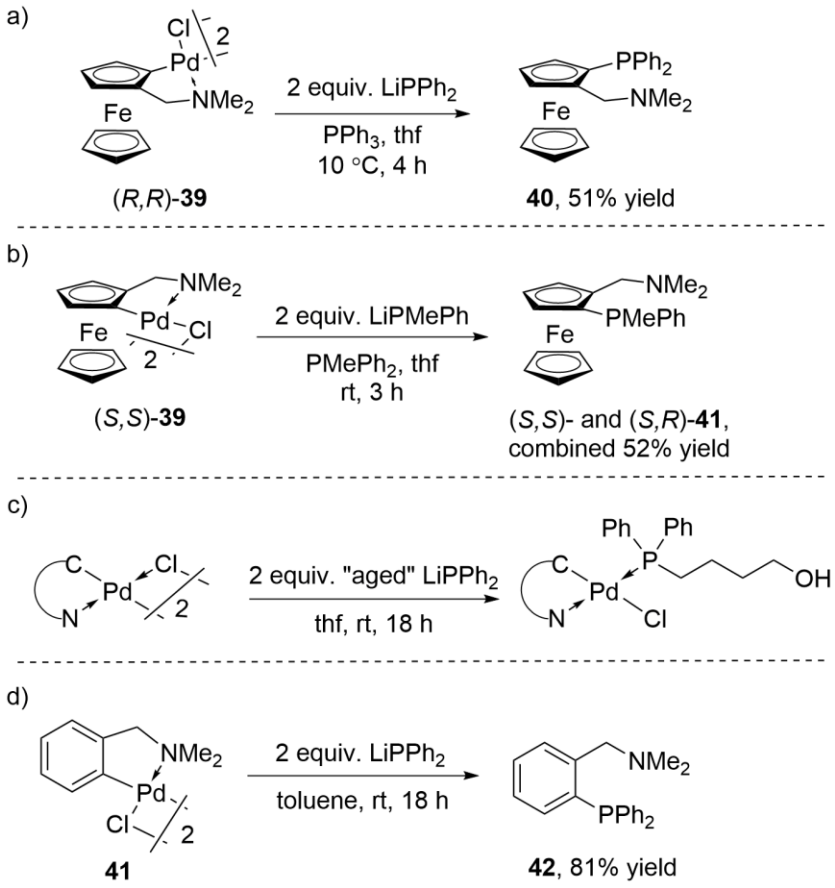


Scheme 12. Cyclopalladation followed by C–PR_2 bond formation.

I.4.2. Reactions with $LiPPh_2$

The first introduction of the PPh_2 group to cyclopalladated ligands was reported by Sokolov et al. in 1980[50] with the reaction of $LiPPh_2$ and a complex derived from 2-*N*,*N*-dimethylaminomethylferrocene [(*S*,*S*)-**39**, Scheme 13a]. A similar study was published by the same group in 1999[51] using LiPMePh (Scheme 13b). Dunina et al. have studied the synthesis of aminophosphine Pd(0) complexes resulting from the reaction of chiral CPCs and $LiPPh_2$.[52] Members of our group have since investigated the influence of $LiPPh_2$

preparation method and time of storage on transformations with a number of structurally diverse CPCs.[53] It was shown that "aged" $LiPPh_2$ solutions in tetrahydrofuran (thf), including those purchased from Sigma Aldrich Co., reacted with dimeric CPCs to give thf ring opening products (Scheme 13c). When the phosphide was freshly prepared from $ClPPh_2$ and Li, the reaction with CPC **41** in toluene provided aminophosphine **42** in 81% yield (Scheme 13d).

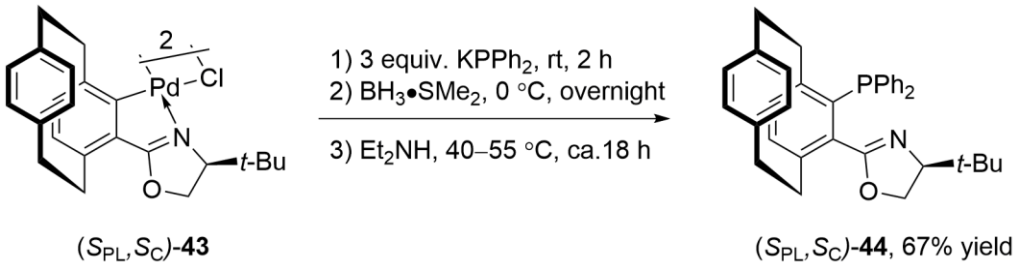


Scheme 13a–d. Reactions of lithium phosphides with *C,N* CPCs.[50, 51, 53]

I.4.3. Reactions with $KPPh_2$

A few drawbacks are associated with lithiated reagents, including high sensitivity to reaction conditions, their higher cost than corresponding potassium phosphides and their

tendency to form aggregates,[53] whereas $KPPh_2$ is monomeric in solution, allowing for more reproducible results. In 2002, Bolm et al. reported a phosphination reaction using $KPPh_2$ and a paracyclophane-derived CPC with an sp^2C–Pd bond (Scheme 14).[54] This study encouraged our group to investigate the use of $KPPh_2$ for the preparation of functionalized phosphines.

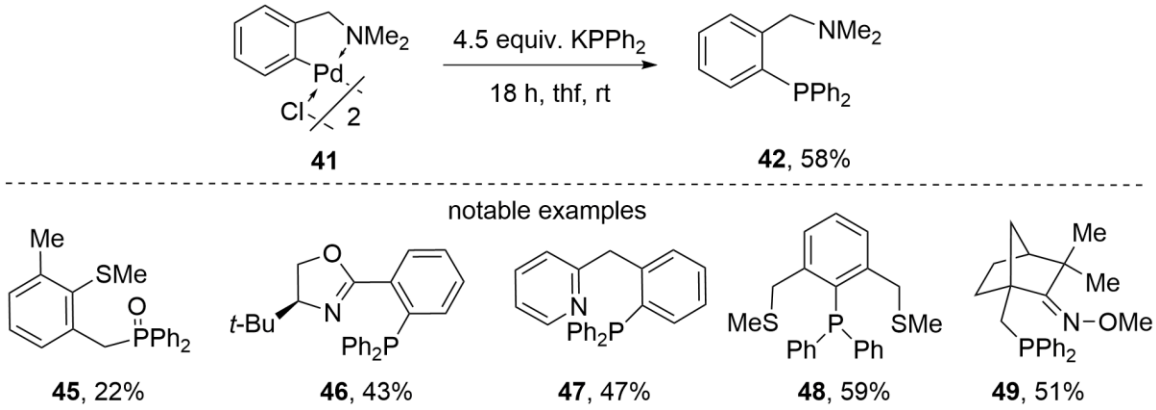


(S_{PL},S_C)-**43** (S_{PL},S_C)-**44**, 67% yield

Scheme 14. Reaction between $KPPh_2$ and paracyclophane-derived CPC (S_{PL},S_C)-**43**.[54]

In 2011, conditions were reported for aminophosphine synthesis using $KPPh_2$ and cyclopalladated *N*,*N*-dimethylbenzylamine **41** (Scheme 15),[55] and in the interest of testing the broad applicability of the $KPPh_2$ approach, our group has recently undertaken two studies involving CPCs with an sp^2C–Pd bond[56] and comparatively rare "aliphatic" complexes with an sp^3C–Pd bond.[57] In the first study, aminophosphines, sulfidophosphines, phosphino-oxazolines, diphosphines, and tridentate *S*,*P*,*S* ligands were obtained from dichloro-bridged dimeric *C*,*N*, *C*,*S* and *C*,*P* CPCs with an sp^2C–Pd bond in five- and six-membered palladacycles (Scheme 15). The phosphination of one *S*,*C*,*S* pincer complex was also described. The results obtained using commercial $KPPh_2$ were identical to those obtained with the reagent freshly prepared from K and $ClPPh_2$, a significant improvement over the observed sensitivity of the reaction to the $LiPPh_2$ preparation method. It was also noted that yields of desired products compared favorably with previously reported multistep procedures and those involving lithiation for the introduction

of the PPh_2 group. Using the same conditions, $KPPh_2$ was reacted with structurally diverse CPCs containing an sp^3C–Pd bond, including novel enantiopure complexes derived from L-fenchone and D-camphor.[58, 59] The bidentate aminophosphines and related hemilabile ligands (or the corresponding phosphine oxides) isolated in the study cannot be obtained by traditional methods, although the yields were lower (20–51%, 5 examples) than those obtained for the analogous transformations using CPCs with an sp^2C–Pd bond.



Scheme 15. Phosphination of CPCs with $KPPh_2$.[55, 56]

I.5. Synthesis of P-Heterocycles

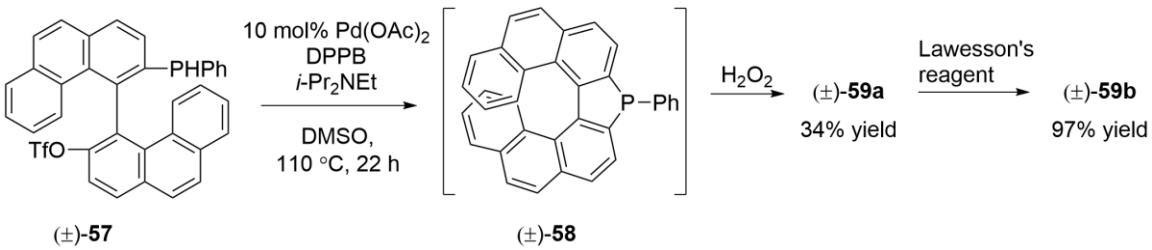
I.5.1. Background

Conjugated phospholes and other *P*-heterocycles have attracted interest for their promising applications as materials for organic light-emitting diodes, organic photovoltaics, and an assortment of optical sensors.[10, 60] The pyramidal geometry of the phosphorous atom in phospholes results in weak aromaticity,[61] which sets these compounds apart from their five-membered *N*-, *S*-, and *O*-heterocyclic counterparts. They are a handle for several types of alterations that affect electronic properties, including synthetically simple ones, such as chalcogenation, boronation, metalation, alkylation, and changing the identity of the substituent[62] Apart from their use in materials, they have also

been studied extensively as monodentate ligands in transition-metal catalysis and as organocatalysts.[63] Synthetic methods for the preparation of phosphorous heterocycles as well as their more recent applications have been discussed thoroughly in reviews by Hibner-Kulicka and Matano.[64, 65] Here the most recently reported synthetic procedures involving palladium will be considered.

I.5.2. Intramolecular C–P Bond Formation

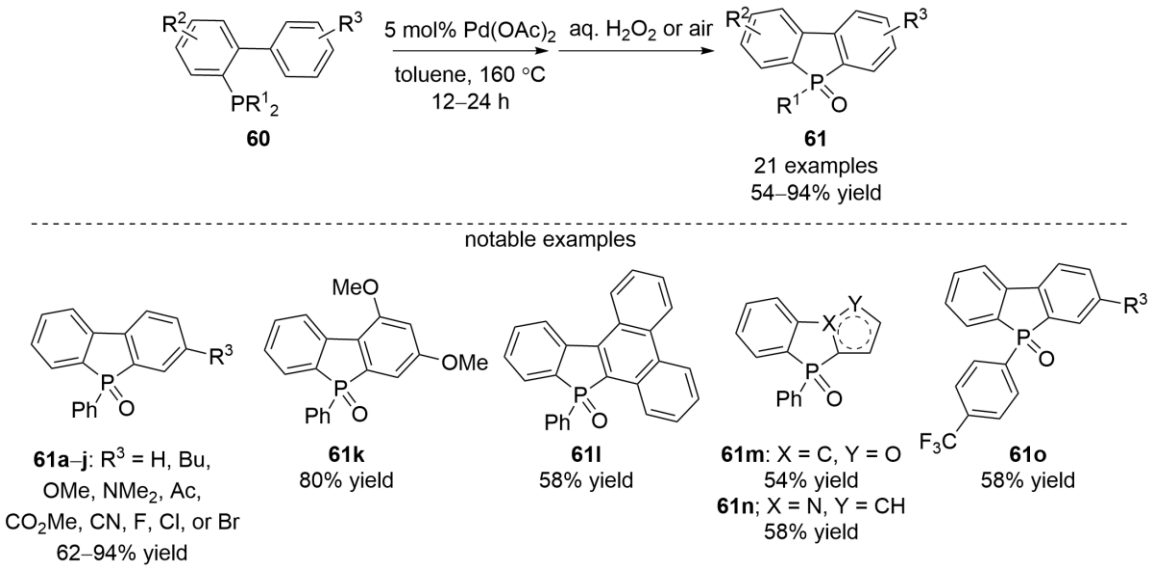
Nakano and coworkers have reported the preparation of λ^5-phospha[7]helicenes, a new family of helicenes, employing catalytic intramolecular C–P bond formation (Scheme 16).[66] Triflate (±)-**57** was synthesized in two steps by Pd-catalyzed coupling of the corresponding bis(triflate) with ethylphenyl phosphinate, HP(O)(OEt)Ph, followed by reduction with $LiAlH_4$. Intramolecular cyclization of the triflate was catalyzed by $Pd(OAc)_2$ in the presence of 1,4-bis(diphenylphosphino)butane (DPPB), and product (±)-**58** was subsequently oxidized to obtain phosphine oxide (±)-**59a**. Enantiomers of the phosphine oxide were separated by HPLC, then pure (*P*)- and (*M*)-**59a** were converted to the corresponding enantiopure sulfides **59b** using Lawesson's reagent. Crystallographic analysis showed unique packing structures for the racemic mixture of **59b**. The (*P*) and (*M*)-enantiomers separated into alternating columnar packing structures having dipole moments in the opposite direction to one another.



Scheme 16. Synthesis of λ^5-phospha[7]helicenes (±)-**59a,b** via Pd-catalyzed intramolecular C–P coupling.[66]

I.5.3. C–P Bond Cleavage Methodologies

Baba and coworkers have developed a Pd-catalyzed phosphole synthesis from tertiary phosphines by sequential C–P bond formation and cleavage.[67] PAr_3 had previously been used as an aryl group source in Pd-catalyzed reactions.[68-70] Specifically, a method for the synthesis of phosphines has been reported via the coupling of aryl triflates and bromides with PR_3.[71-74] However, the study by Baba was the first investigation focused on the use of PAr_3 for preparation of phospholes (Scheme 17). It is worth noting that a broad variety of triarylphosphines are commercially available and air-stable, and that the reaction displays high functional group tolerance. The authors obtained the phospholes at high temperature (160 °C) in good yields. They offered experimental evidence to support a proposed mechanism that includes the formation of CPC **62** followed by reductive elimination and then dearylation through oxidative addition to Pd(0) (Figure 3).



Scheme 17. Pd(II)-catalyzed synthesis of phospholes using tertiary phosphines.[67]

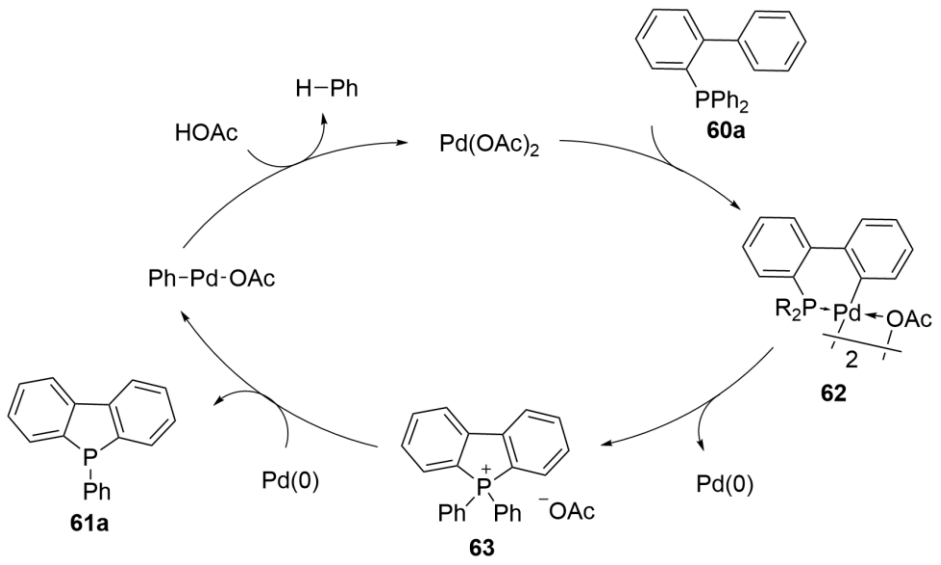
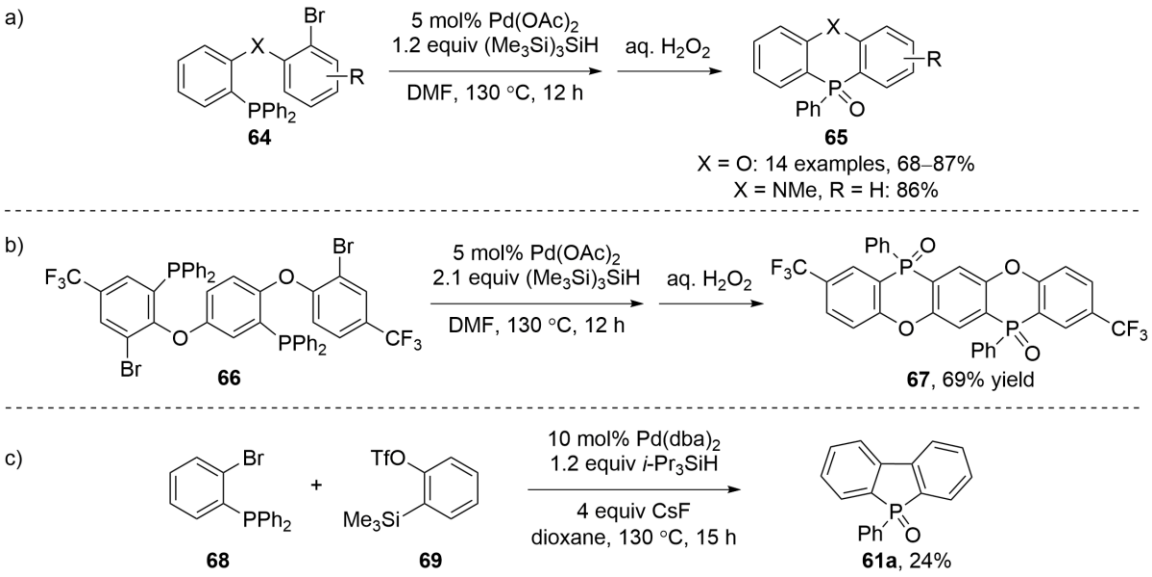


Figure 3. Mechanism for phosphole synthesis proposed by Baba and coworkers.[67]

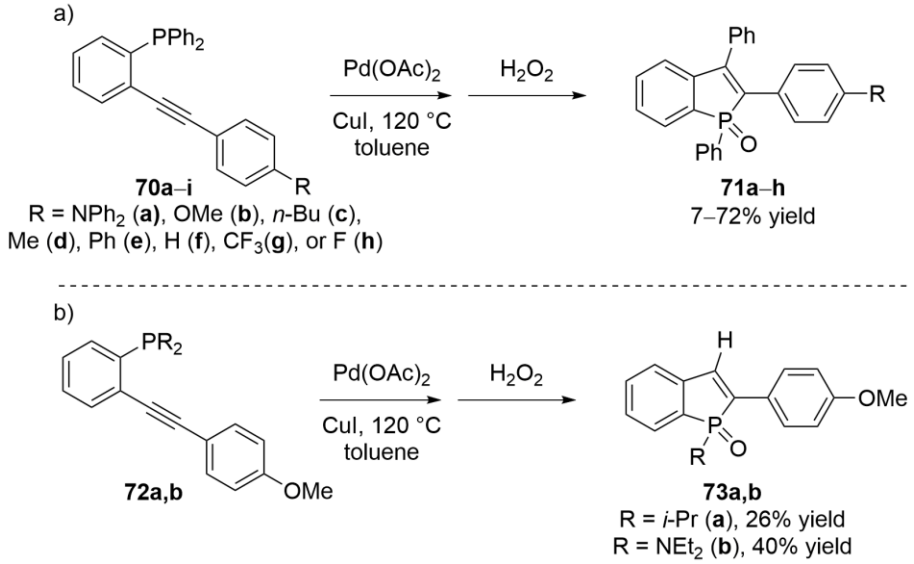
In a subsequent article, Baba and coworkers applied a similar methodology to prepare six-membered phospholes.[75] However, starting bromides were needed to facilitate the formation of a seven-membered palladacycle intermediate, and hydrosilanes were added to induce reductive elimination from Ph–Pd–Br and regenerate the catalyst (Scheme 18a). Bulkier hydrosilanes were more effective, with $(Me_3Si)_3SiH$ giving yields between 68% and 87% for the model reaction. The authors described the formation of compound **67** having a ladder-type structure (Scheme 18b) to illustrate the accessibility to extended heterocycles. Intermolecular reactions could offer a more straightforward path to extended π-systems, thus similar conditions were used in the reaction of bromophosphine **68** and the benzyne precursor **69** as a proof-of-concept (Scheme 18c).



Scheme 18a–c. a) Synthesis of six-membered phospholes. b) Formation of extended heterocycles. c) Intermolecular cyclization via benzyne intermediate.

Zhou and coworkers have developed an alternative Pd/Cu-catalyzed phosphole synthesis.[76] The method can be viewed as a P–Ph addition to a C≡C bond, analogous to the previously reported P–H addition to alkynes.[25, 36] The reaction requires catalytic amounts of Cu(I) salts along with Pd, as neither metal alone gave cyclization products under the conditions shown in Scheme 19. The presence of electron-withdrawing or -donating substituents in the para positon of the alkyne Ar group was found to have a significant effect on phosphole formation. Lower yields of products were observed for alkynes with *p*-$NPh_2C_6H_4$ and *p*-$MeOC_6H_4$ substituents (**70a,b**; Table 5, entries 1–3) and higher yields were achieved for compounds with electron-withdrawing *p*-$CF_3C_6H_4$ and *p*-FC_6H_4 groups (**70g,h**; entries 8 and 9). Alkyne **70i** (Ar = 1-naphthyl) did not give the desired product, an indication that bulky groups interfere with the cyclization process. The authors also reported the reactions of diisopropyl-substituted phosphine **72a** and bis(diethylamino)-substituted phosphazane **72b** (Scheme 19b; entries 11 and 12). Although the cyclizations

were observed, the *β*-elimination products were also isolated from reaction mixtures. It is noteworthy that the formation of **73a** constitutes the first reported case of a Pd(0)-catalyzed sp^3C–P bond cleavage.



Scheme 19a,b. a) Synthesis of monobenzofused phospholes **71a–h**. b) Synthesis of compounds **73a,b**.

Table 5. Results of the reaction depicted in Scheme 19.

Entry	Product	R	Yield (%)	Entry	Product	R	Yield (%)
1	**71a**	NPh_2	7	7	**71f**	H	41
2*	**71a**	NPh_2	29	8	**71g**	CF_3	68
3	**71b**	OMe	32	9	**71h**	F	72
4	**71c**	*n*-Bu	43	10†	**71i**	NA	0
5	**71d**	Me	52	11	**73a**	*i*-Pr	26
6	**71e**	Ph	45	12	**73b**	NEt_2	40

*$Pd(PPh_3)_2Cl_2$ was used instead of $Pd(OAc)_2$.
†1-Napthyl instead of *p*-RC_6H_4.

I.6. Conclusions

Palladium-assisted methods for the formation of the C–PR_2 (R = alkyl or aryl group) bond have been surveyed. In recent reports, the synthesis of tertiary phosphine ligands with different types of chirality has been a focal point. This task has been

approached from multiple directions including the use of chiral catalysts and achiral reactants in the case of palladacycle-catalyzed hydrophosphinations. Stereoconvergent methods utilizing dynamic kinetic resolution have been applied to the synthesis of enantio-enriched *P,N* ligands with axial chirality. Readily available enantiopure and achiral cyclopalladated complexes with either an sp^3C–Pd or sp^2C–Pd bond in five- and six-membered *C,N*, *C,S* and *C,S* palladacycles have been used in reactions with metal phosphides and secondary phosphines to furnish unique hemilabile bidentate ligands, which are often not easily accessible by other known methods. Aside from the preparation of non-cyclic PR_3 products, the synthesis of phospholes has been achieved using Pd-catalyzed intramolecular couplings of secondary and tertiary phosphines.

In addition, recent studies of phosphole synthesis have described Pd-catalyzed C–P bond cleavage in phosphonium intermediates to form a new C–PR_2 bond. In all but one case the cleaved bond was sp^2C–P, which leaves the door open for further study of sp^3C–P bond cleavage. The possibility of intermolecular cyclization leading to a *P*-heterocycle has also been demonstrated, and provided a yet-to-be-explored avenue towards the Pd-catalyzed synthesis of phosphole polymers with potential in the field of electronics.

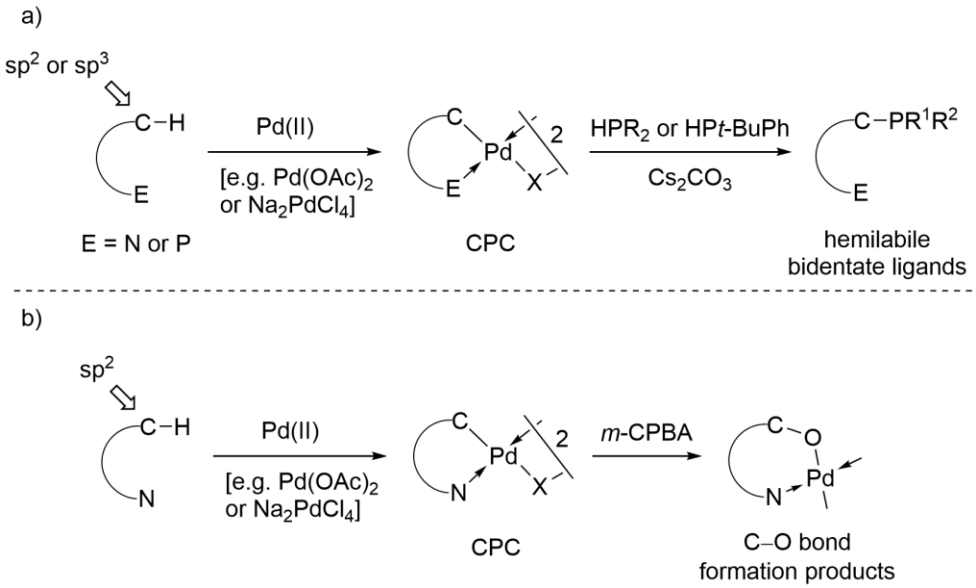
It is noteworthy that so far researchers in the field of Pd-mediated C–PR_2 bond formation have rarely reported the use of phosphine reagents with bulky or non-equivalent substituents. Tuning steric properties of the substituents directly connected to the *P* atom and introducing *P*-chirality in tertiary phosphines are certain to influence the reactive center in transition metal-catalyzed reactions employing tertiary phosphines. There is no doubt that development of simple and general methods for the preparation of enantiopure phosphines with an sp^2 and sp^3C–PR_2 bond and having different types of chirality will

remain an important task in synthetic organic chemistry. It is also likely that the use of Pd in new methods of C–P bond formation will be expanded to include more examples of these challenging reactions.

I.7. Goals of the Proposed Study

There are several known approaches for the synthesis of aminophosphines and related bidentate ligands; some of them were outlined in the previous section of this chapter. However, the diversity of these compounds is limited at present due to a reliance on specific types of reactants, many of which are difficult to synthesize. In this dissertation, new methods for the synthesis of tertiary phosphines were proposed, specifically those with an sp^3C–P bond and an additional donor atom, using reactions of CPCs with $HPPh_2$. The steric and electronic effect with a variety of secondary phosphines was investigated, including a prochiral phosphine, HP*t*-BuPh, on CPCs with either an sp^2 or sp^3C–Pd bond. Also, a method was proposed for C–O bond formation through the reaction of CPCs with *meta*-chloroperoxybenzoic acid (*m*-CPBA).

The general methodology encompassing all three proposed studies can be summarized as a two-step approach (Scheme 20). In the first step, suitable preligands are cyclopalladated with a Pd(II) source to form dimeric chloro- or acetato-bridged complexes. The C–Pd bond of the products are then transformed to a C–P (Scheme 20a) or C–O (Scheme 20b) bond with secondary phosphines or the oxidizing agent *m*-CPBA, respectively.



Scheme 20a,b. a) Two-step method for the synthesis of hemilabile bidentate ligands. b) Method for regioselective C–O bond formation.

There are several goals of this study: i) to develop a method for sp^3C–P bond formation using CPCs and secondary phosphines, ii) to synthesize a set of structurally unique tertiary phosphines, iii) to study the electronic and steric effect of HPR_2 on phosphination reactions with sp^2 and sp^3C–Pd CPCs, iv) to study the stereoselectivity of the transformation using HP*t*-BuPh, v) to develop a related C–O bond formation method using CPCs and *m*-CPBA, and vi) to characterize all new compounds by spectroscopic methods.

CHAPTER II

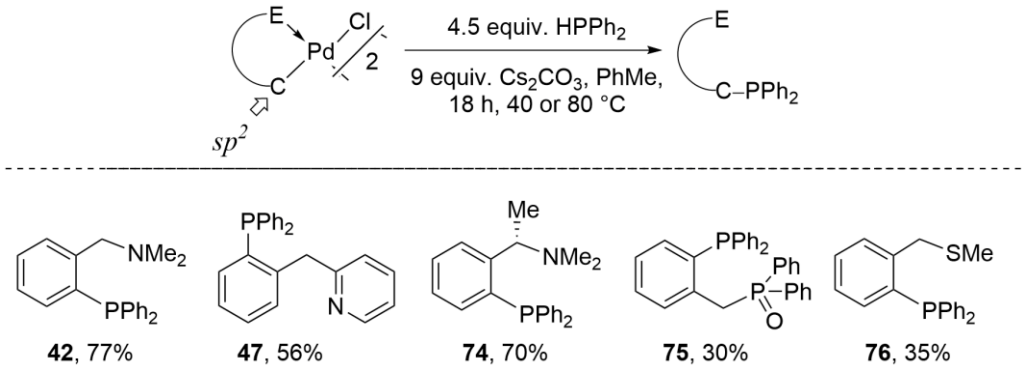
RESULTS AND DISCUSSION

II.1. Reactions of Cyclopalladated Complexes with $HPPh_2$

II.1.1. Background

The use of secondary phosphines in C–PR_2 bond formation is desirable compared to the use of metal phosphides for several reasons. First, as the precursors to lithium and potassium phosphides, they have a relatively low cost. They are also soluble in a variety of solvents, including non-polar ones. Finally, whereas air-sensitive MPR_2 (where R ≠ Ph) generally need to be synthesized in the lab, there is a broad variety of secondary phosphines available commercially.

Before the beginning of this work, our group had unpublished data regarding the phosphination of sp^2*C,E* ligands using $HPPh_2$. In the reaction of cyclopalladated *N,N*-dimethylbenzylamine, varying the molar ratio of CPC:$HPPh_2$ (2, 4.5, and 9), solvent (thf, PhMe, and CH_2Cl_2), temperature (rt, 40, 60, and 80 °C), time of experiment (1, 1.5, 3, 4, and 18 h), and base (NaOAc, K_2CO_3, K_3PO_4, Cs_2CO_3, and $NaOSiMe_3$), led to conditions for the isolation of aminophosphine **42** in 77% yield (Scheme 21). This methodology was applied for the synthesis of enantiopure **74**, aminophosphine **47** (obtained from the reaction of a six-membered CPC), sulfidophosphine **75**, and diphosphine monoxide **76**.

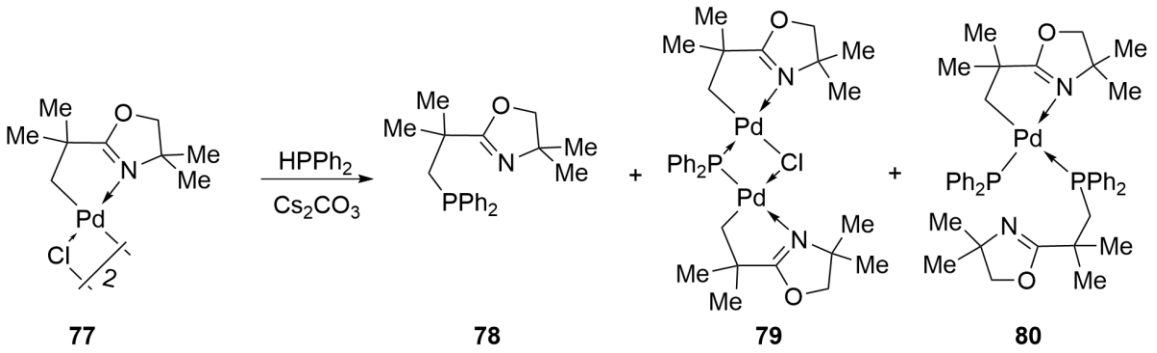


Scheme 21. Optimized conditions of the reaction between sp^2C–Pd CPCs and $HPPh_2$.

II.1.2. Reactions at the sp^3*C–Pd Bond*

While introduction of the PAr_2 group to an aromatic ring is usually accomplished via the lithiation of appropriate substrates, the basic method for the formation of an sp^3C–P bond is the S_N2 reaction of a metal phosphide with alkyl halides or related compounds having good leaving groups.[6] Recently, a method for sp^3C−P bond formation using $KPPh_2$ reactions with CPCs having an sp^3C−Pd bond was reported.[57] Based on the results of that study, it was predicted that phosphination of cyclopalladated ligands at an sp^3-hybridized carbon could also be accomplished using $HPPh_2$.

The previously reported[77, 78] *C,N* CPC **77** derived from 2-*tert*-butyl-4,4-dimethyl-2-oxazoline was chosen as a model compound to determine the optimal conditions for phosphination reactions leading to the formation of an sp^3C−P bond. The complex reacted with $HPPh_2$ in the presence of Cs_2CO_3 in toluene at 40 °C; however, no signals of free iminophosphine **78** were detected in the $^{31}P\{^1H\}$ NMR spectrum of the crude mixture. Instead, complexes **79** and **80** were isolated in 24 and 52% yield, respectively (Scheme 22). After varying reaction conditions (Table 6), the best yield of iminophosphine **78**, 56%, was obtained using 9 equivalents of $HPPh_2$ in CH_2Cl_2 at 35 °C (entry 7).



Scheme 22. Reactions of $HPPh_2$ with CPC **77** having an sp^3C−Pd bond.

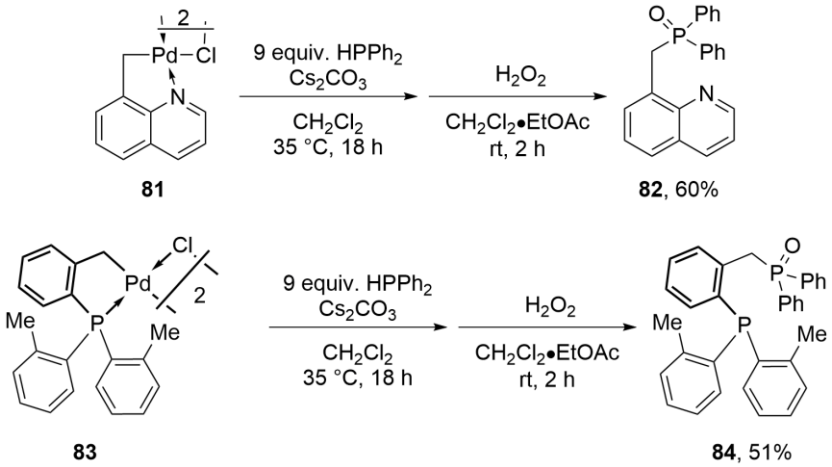
Table 6. Yields of compounds **78**−**80** depending on the condition used.

Entry	$HPPh_2$, equivalents	Solvent	T, °C	Time, h	Yield, %		
					78	**79**	**80**
1	4.5	PhMe	40	18	0	24	52
2	4.5	PhMe	80	18	18	0	29
3	9	PhMe	rt	48	13	0	33
4	9	PhMe	40	18	15	0	15
5	9	PhMe	80	18	25	0	18
6	4.5	CH_2Cl_2	35	18	18	0	18
7	9	CH_2Cl_2	35	18	56	0	0
8	4.5	thf	40	18	0	0	15
9	2	thf	40	18	0	14	14

Complex **79** was previously reported as a product in the reactions of CPC **77** with $KPPh_2$.[57] The structure of the novel complex **80** was determined with ^1H, $^{13}C\{^1H\}$, DEPT, $^{31}P\{^1H\}$ and 2D NMR spectroscopy. According to the NMR data, compound **80** contains a *C,N* cyclopalladated ligand of the starting reagent **77**, iminophosphine **78** as a monodentate auxiliary ligand, and a terminal PPh_2 ligand. The presence of two PPh_2 groups in the complex and their cis geometry are supported by the presence of two doublets in the $^{31}P\{^1H\}$ NMR spectrum at δ 7.8 and 116.8 ppm with coupling constant $^2J_{PP}$ = 38 Hz.[79-81] The signal at δ 116.8 ppm was assigned to the PPh_2 ligand; the low-field position of the doublet suggests non-bridging coordination of this ligand to the metal.[82] The cis position

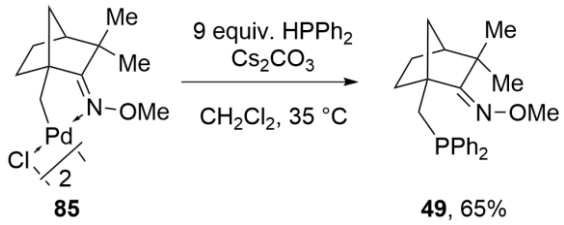
of the CH_2 fragment of the cyclopalladated ligand and the terminal PPh_2 ligand in complex **80** is suggested based on the transphobia concept.[83, 84] There are several reports of mononuclear Pd(II) complexes containing a terminal phosphido group. Zhuravel et al. and Mazzeo et al. have reported complexes in which the P–Pd bond was stabilized by intramolecular chelation of the ligand.[79, 82] Madadi et al. have recently reported disilyl- and dibenzoylphosphido complexes of type PdI(*i*-Pr_2-bimy)$_2PR_2$ and PdI(*n*-Bu_2-bimy)$_2PR_2$, which are stabilized by the presence of *N*-heterocyclic carbene ligands.[85] Moncarz et al. as well as Pican and Gaumont isolated phosphido-borane complexes with the structure Pd(L)(Ar)P(BH_3)R^1R^2 (L = diphos or another *P*,*P* or *P*,*N* ligand).[86-88] Mononuclear *κ*-PPh_2 Pd(II) complexes were proposed as intermediates in Pd-catalyzed phosphination reactions,[31, 89] but they have not been isolated to our knowledge.

To examine the reactivity of other aliphatic CPCs, complexes **81** and **83** containing benzylic C–Pd bonds were reacted with 9 equivalents of $HPPh_2$ in CH_2Cl_2 at 35 °C. In both cases, partial oxidation of the ligand was observed. The crude mixtures were therefore oxidized prior to purification either with 30% H_2O_2 or by exposure to air providing phosphine oxides **82** and **84** in 60% and 51% yield, respectively (Scheme 23).



Scheme 23. Reactions of complexes **81** and **83** with $HPPh_2$.

Our group has previously reported the preparation of CPC **85** derived from the *O*-methyloxime of L-fenchone[58] and its subsequent reaction with $KPPh_2$ at rt in thf.[57] In those reactions, the corresponding free *N,P* ligand **49** was isolated in 51% yield whereas the reaction with 9 equivalents of $HPPh_2$ in CH_2Cl_2 at 35 °C gave an improved 65% yield (Scheme 24).

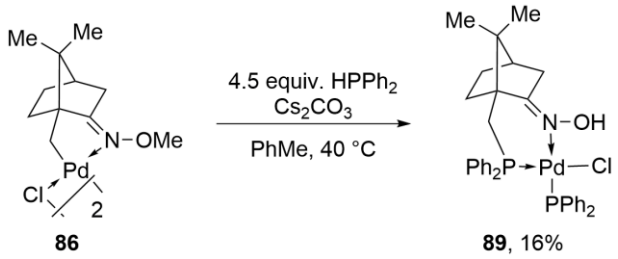


85 **49**, 65%

Scheme 24. Reaction of CPC **85** with $HPPh_2$ to form product **49**.

The preparation of CPC **86** derived from the *O*-methyloxime of D-camphor[59] was also reported along with its reactions with $KPPh_2$,[57] furnishing the corresponding free *N,P* ligand (**87**) in 21% yield while its oxide (**88**) was not isolated. By contrast, in reactions of complex **86** with 9 equivalents of $HPPh_2$ in the presence of Cs_2CO_3 in CH_2Cl_2 (both at rt and 35 °C) no signal of the *N,P* ligand was observed in $^{31}P\{^1H\}$ NMR spectra of the crude mixtures or isolated fractions. When the optimized conditions for the phosphination of CPC **41** were used, the major product was found to be the unique Pd(II) complex **89**. The compound contains a terminal PPh_2 group, a chloride ligand, and an *N,P* ligand. The ^1H NMR spectrum provided evidence that the NOMe group in the cyclopalladated ligand was converted to NOH, with the oxime signal appearing at 9.02 ppm. The $^{31}P\{^1H\}$ NMR spectrum of the complex contained two doublets with a rather small coupling constant (12.2 Hz), suggesting the cis position of two *P* atoms (Scheme 25).[55] An interesting feature of the $^{13}C\{^1H\}$ NMR spectrum is the long-range coupling observed between the terminal

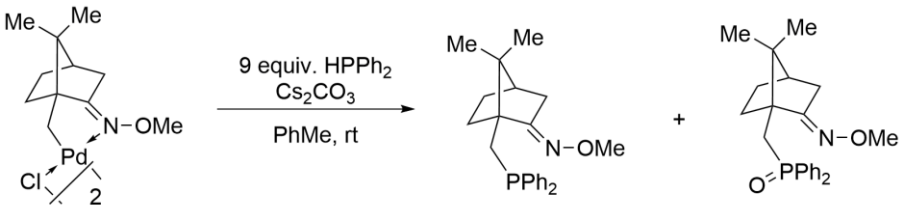
phosphido group and C3 of the camphor bicycle ($^4J_{CP}$ = 4.8 Hz). HRMS data confirmed the presence of a cation corresponding to complex **89** minus a chloride ion. The proposed structure was further supported by testing the substance for halides using $AgBF_4$, after which a precipitate was observed.



86 **89**, 16%

Scheme 25. Reaction of CPC **86** with $HPPh_2$ furnishing complex **89**.

In an attempt to free the *N,P* ligand from coordination with palladium, the workup was altered by addition of 1,2-bis(diphenylphosphino)ethane at the end of the reaction; however, this was not effective. A series of experiments were then performed where one parameter of the reaction conditions was changed: different temperatures (rt, 40 °C, and 80 °C), solvents (toluene, CH_2Cl_2, and thf), and molar equivalents of $HPPh_2$ (3.2, 3.9, 4.5, and 9) were explored. However, the free *N,P* ligand was not isolated in any of these experiments with only one exception. At rt with 9 equivalents of $HPPh_2$ in toluene, oximophosphine **87** was obtained in 21% yield along with the oxidized analog **88** (9%, Scheme 26). Noteworthy, the *N,P* ligand was not isolated from reactions in toluene using the same ratio of reactants at 40 °C and 80 °C.



86 **87**, 21% **88**, 9%

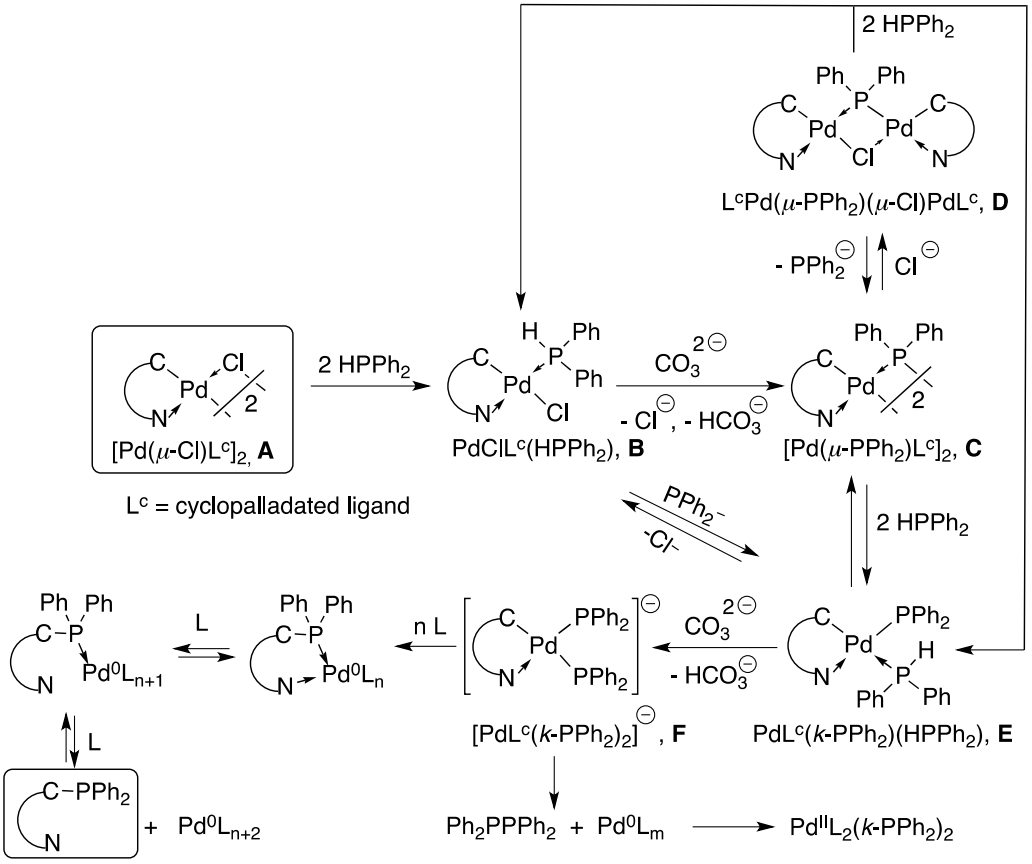
Scheme 26. Preparation of compounds **87** and **88**.

The yields of *N,P* ligands **78**, **82**, and **49** as well as the phosphine oxide **84** (56−65%) obtained in this study were consistently higher than those reported for the related $KPPh_2$ reactions with CPCs having an sp^3C−Pd bond.[57] It is noteworthy that the alternative method for the phosphination of the alkyl fragment, based on the S_N2 reaction of alkyl halides with metal phosphides, was successfully used for preparation of enantiopure phosphino-oxazolines.[90] However, a major obstacle to the generality of this method for preparation of bidentate hemilabile ligands is the need for regioselective halogenation of the alkyl moiety before the phosphination step.

II.1.4. Mechanistic Considerations

It is suggested that the first step of the reaction between $HPPh_2$ and complex $[Pd(\mu\text{-}Cl)L^C]_2$ (structure **A** in Scheme 27 where L^C is a cyclopalladated ligand) is the formation of the corresponding mononuclear CPC, $PdClL^C(HPPh_2)$ (**B**). The $^{31}P\{^1H\}$ NMR spectra of the 1:2.5 and 1:4.5 mixtures of CPC **77** and $HPPh_2$ in toluene-d_8 (recorded at 20 °C after freezing to –95 °C) contained a prominent signal at δ –1.2 ppm. This signal was assigned to the *P* atom of $HPPh_2$ in $PdClL^C(HPPh_2)$ (L^C = cyclopalladated 2-*tert*-butyl-2,2-dimethyl-2-oxazoline). Although there are several known Pd(II) complexes with $HPPh_2$ as a terminal ligand,[31, 80, 91, 92] to the best of our knowledge, there has been only one report of an analogous *C,N* cyclopalladated complex.[93] Díez et al. described the preparation and spectral characterization of an $HPPh_2$ adduct of benzo[*h*]quinoline-derived CPC $PdCl(bzq^C)(HPPh_2)$. The reported ^{31}P NMR data of the complex include the chemical shift, 20.2 ppm, and the coupling constant, $^1J_{PH}$ = 376 Hz. In non-decoupled ^{31}P NMR spectra of CPC **77**/$HPPh_2$/Cs_2CO_3 reaction mixtures, the proposed complex $PdClL^C(HPPh_2)$ (L^C =

cyclopalladated 2-*tert*-butyl-2,2-dimethyl-2-oxazoline) gave a broad doublet with a coupling constant $^{1}J_{PH}$ = 375 Hz.



Scheme 27. Proposed mechanism of *N*,*P* ligand formation by reaction of CPC with $HPPh_2$.

Díez et al. also prepared the Pt analog $PtCl(bzq^{C})(HPPh_2)$, which was converted to $[Pt(\mu\text{-}PPh_2)(bzq^{C})]_2$ in the presence of K_2CO_3.[93] By analogy, it is suggest that in the presence of Cs_2CO_3 or another base, complexes of type **B** undergo a transformation to $[Pd(\mu\text{-}PPh_2)L^{C}]_2$ (**C**, Scheme 27). Previously, it was shown that in the presence of chloride ions, the diphosphido-bridged complex $[Pd(\mu\text{-}PPh_2)L^{C}]_2$ (**C**) derived from 2-*tert*-butyl-4,4-dimethyl-2-oxazoline is converted to the corresponding mono-chloro-mono-phosphido-bridged analog, $L^{C}Pd(\mu\text{-}PPh_2)(\mu\text{-}Cl)PdL^{C}$ (**D**), and a small amount of the trinuclear

complex $L^C Pd(\mu\text{-}PPh_2)(\mu\text{-}Cl)Pd(\mu\text{-}PPh_2)(\mu\text{-}Cl)PdL^C$.[57] So, it is reasonable to suggest that CPC/$HPPh_2$/Cs_2CO_3 reaction mixtures should also contain complexes of type **D** (Scheme 27) and possibly trinuclear derivatives $L^C Pd(\mu\text{-}PPh_2)(\mu\text{-}Cl)Pd(\mu\text{-}PPh_2)(\mu\text{-}Cl)PdL^C$ (the latter complex is not shown).

In the presence of an additional 2 equivalents of $HPPh_2$, complex $[Pd(\mu\text{-}PPh_2)L^C]_2$ (**C**) is expected to give $PdL^C(\kappa\text{-}PPh_2)(HPPh_2)$ (**E**), whereas $L^C Pd(\mu\text{-}PPh_2)(\mu\text{-}Cl)PdL^C$ provides two complexes, **E** and **B** (Scheme 27). Complex **E** may also be formed from its chloro-analog **B** in the presence of PPh_2 ions or, perhaps more likely, from the Pd(II) phosphido complexes **C** and **D**, since $HPPh_2$ (pK_a 22.9 in DMSO)[94] cannot be deprotonated by Cs_2CO_3 (HCO_3^- has pK_a 10.3) without prior coordination to palladium. This is supported by the fact that the ^{31}P NMR spectra of $HPPh_2$ with or without Cs_2CO_3 are identical.

The last step of the phosphination reaction is expected to be reductive elimination. The isolation of $Pd(HPPh_2)_4$ from a reaction mixture of CPC **41** with 4.5 equivalents of $HPPh_2$ in the presence of Cs_2CO_3 supports reductive elimination of $Pd(0)L_n$ from a Pd(II) intermediate. The formation of this and other Pd(0) species containing $HPPh_2$ as a ligand may explain why an excess of the reactant is needed. In general, all complexes having a PPh_2 ligand cis to a C–Pd bond (e.g., compounds **C**–**F**) could be considered as species that potentially undergo reductive elimination. However, there is some indication that the complexes with a bridging PPh_2 ligand, **C** and **D**, are unlikely to go through reductive elimination to produce an *N,P* ligand. In our previous study,[53] it was found that complex **D** derived from *N,N*-dimethylbenzylamine slowly undergoes reductive P–P coupling in CH_2Cl_2 at rt to produce $Ph_2P–PPh_2$, the mononuclear complex $LPd^{II}Cl[PPh_2P(O)Ph_2]$ and

Pd(0) black. In another study,[57] it was shown that at rt in the presence of chloride ions, two diphosphido-bridged complexes of type **C** derived from D-camphor *O*-methyloxime and 2-*tert*-butyl-2,2-dimethyl-2-oxazoline readily undergo ligand metathesis instead of reductive elimination. Both types of complexes, **C** and **D**, provided *N*,*P* ligands only in the presence of at least one additional equivalent of $MPPh_2$ (M = Li or K).[53, 57] These data suggest that in order to undergo reductive elimination with the formation of a C–P bond, a Pd(II) complex should have a terminal rather than bridging phosphido ligand. In order to have a complex with a terminal PPh_2 group, the CPC/$HPPh_2$/Cs_2CO_3 reaction mixture must have at least 2 equivalents of $HPPh_2$ per palladium atom. The most plausible intermediate that may undergo reductive elimination to give C–P coupling appears to be $[PdL^C(\kappa\text{-}PPh_2)_2]^-$ (**F**, Scheme 27). Related anionic complexes of the type $[PdL^C(\kappa\text{-}OAc)_2]^-$ and $[PdL^CBr_2]^-$ (where L^C is a *C*,*P* CPC with a benzylic sp^3C–Pd bond) have previously been implicated as species undergoing reductive elimination leading to C–O and C–Br bond formation,[95] respectively.

In 1:2.5 and 1:4.5 reaction mixtures of CPC **77** and $HPPh_2$ in the presence of Cs_2CO_3, initial $^{31}P\{^1H\}$ NMR spectra of the mixtures frozen to –95 °C and recorded at rt contained a broad signal at –1.2 ppm, as previously mentioned. As the samples were kept at rt, this signal gave way to a singlet at –1.53 ppm, which was assigned to the previously reported complex of type **D**, $L^CPd(\mu\text{-}PPh_2)(\mu\text{-}Cl)PdL^C$ (L^C = cyclopalladated 2-*tert*-butyl-2,2-dimethyl-2-oxazoline). Two doublets in the $^{31}P\{^1H\}$ NMR spectrum (still doublets in the non-decoupled spectrum) were also observed at 79.0 and 70.9 ppm ($^2J_{PP}$ = 48 Hz) after 14 h when the molar ratio of $HPPh_2$ to CPC was 1:4.5. When the ratio was 1:2.5, these signals were present after 72 h. and were still prominent after ten days, when signals

corresponding to free iminophosphine **78** and complex **80** were first observed. The fact that the C–P coupling products **78** and **80** were not detected until after these two doublets were present suggests that they may belong to a key intermediate from which reductive elimination occurs. The chemical shift value and the proximity of the signals at 79.0 and 70.9 ppm suggest that they belong to similar Pd-bound P-containing groups. The value of the coupling constant, 48 Hz, points to the cis position of these two ligands. It is proposed that these doublets belong to $[PdL^{C}(\kappa\text{-}PPh_2)_2]^{-}$ (L^{C} = cyclopalladated *tert*-butyl-2,2-dimethyl-2-oxazoline). In the case of the 1:4.5 ratio of reactants, signals for complex **80** were present after 18 hours at rt, implying that C–P bond formation is faster with excess $HPPh_2$.

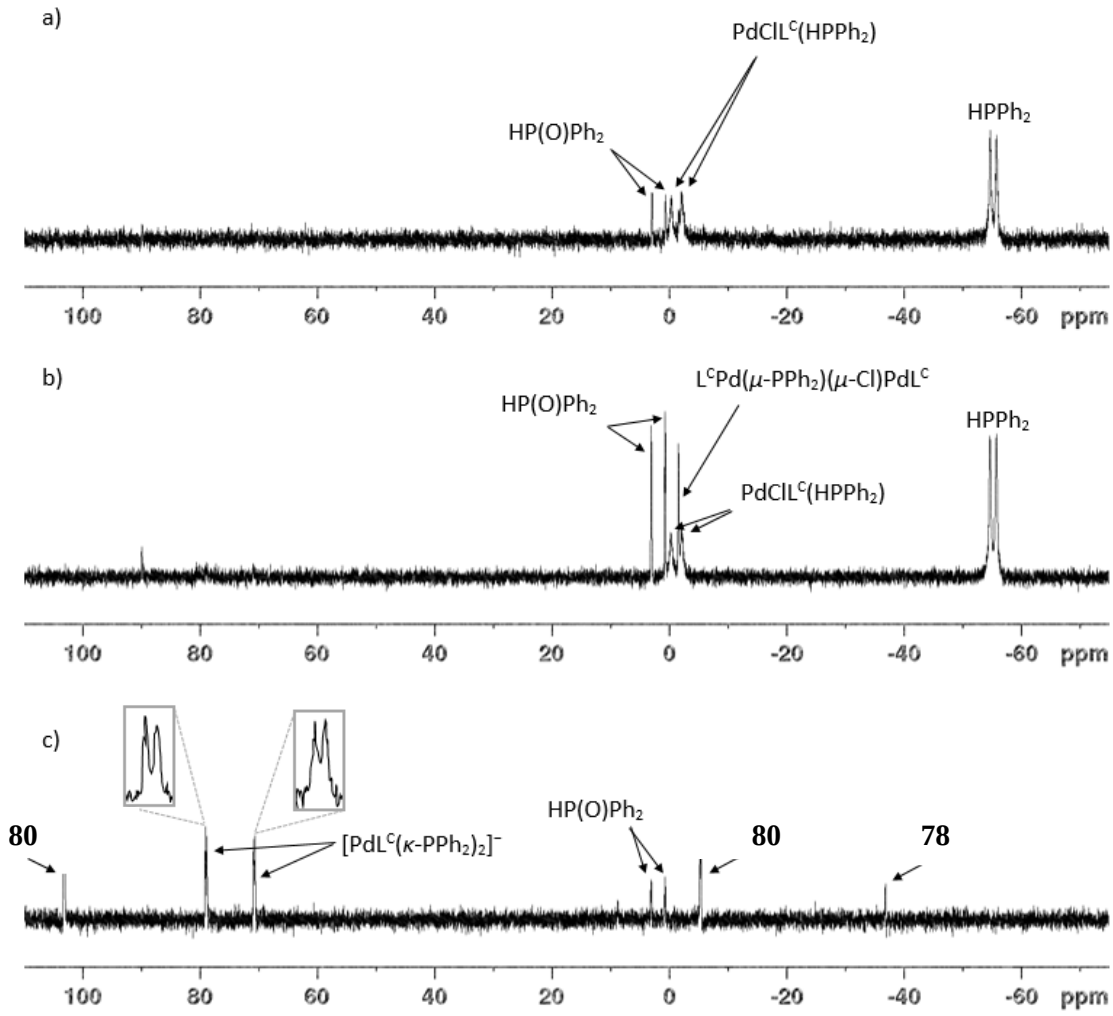


Figure 4. Proton-coupled ^{31}P NMR spectra of CPC **77**/$HPPh_2$/Cs_2CO_3/toluene-d_8 reaction mixtures frozen to –95 °C and kept at rt for: a) 10 min. (4.5 equivalents $HPPh_2$), b) 4 h (4.5 equivalents $HPPh_2$), and c) 10 days (2.5 equivalents $HPPh_2$). (L^C = cyclopalladated *tert*-butyl-2,2-dimethyl-2-oxazoline)

There is no reason to believe that reductive elimination from $[PdL^C(\kappa\text{-}PPh_2)_2]^-$ with an sp^2C–Pd bond takes place through a different route than a traditionally proposed three-membered transition state.[96] To give Pd(0) species, complexes $[PdL^C(\kappa\text{-}PPh_2)_2]^-$ with an sp^2C–Pd bond may actually have two transition states, one with Pd, P and C atoms and the other with Pd and two P atoms, since one of the PPh_2 ligands is cis to both C and P atoms.

Interestingly, products of P–P coupling were observed in the majority of reactions involving CPCs with an sp^2C−Pd bond. $Ph_2PP(O)PPh_2$ was isolated in some of those reactions, and the corresponding adduct of the type $L^CPd^{II}Cl[PPh_2P(O)Ph_2]$ (L^C = cyclopalladated *N*,*N*-dimethylbenzylamine) was also obtained in low yield when $NaOSiMe_3$ was used as a base. However, in the same reactions of CPCs having an sp^3C–Pd bond, neither $Ph_2PP(O)PPh_2$ nor complexes $L^CPd^{II}Cl[PPh_2P(O)Ph_2]$ were isolated or detected. Thus, in reactions with CPCs containing an sp^2C–Pd bond, P–P coupling competes with C–P bond formation during the reductive elimination step. The absence of P–P coupling products in reactions with CPCs having an sp^3C–Pd bond indicates that the S_N2-like mechanism of the reductive elimination step may be favored over the concerted pathway involving a three-atom transition state. In the case of an S_N2 mechanism, the PPh_2 ion is more likely to attack the carbon than the phosphorus atom bonded to two bulky phenyl groups (*vide infra*).

Little is known about the mechanism of the reductive elimination step from Pd(II) complexes to give an sp^3C–E bond, where E = *N*, *P* or *O*.[57, 96-107] Similar to the sp^2C−E couplings, concerted sp^3C–N bond formation through a three-membered transition state has been proposed for the reductive elimination of norbornylamines from alkylpalladium(II) amido complexes.[99] However, an S_N2-like mechanism for our phosphination reactions cannot be excluded. The two most probable S_N2 pathways include 1) nucleophilic attack by the exogenous PPh_2 ion on the sp^3-hybridized carbon bonded to Pd(II) and 2) dissociation of the PPh_2 ligand from a Pd(II) complex, e.g., **F**, followed by S_N2 attack of the phosphide ion on the carbon.

To shed light on possible mechanisms of the reductive elimination step, three experiments were performed with complex **80,** which has a terminal PPh_2 ligand cis to the Pd-bound carbon atom. The compound was heated for 18 h at 75 °C in acetonitrile, at 80 °C in toluene in the presence of 4 equivalents of PPh_3 as an auxiliary ligand, and at 80 °C in toluene with 9 equivalents of Cs_2CO_3 and 4 equivalents of $HPPh_2$. Only in the latter case did the free iminophosphine form (NMR data showed >80% conversion), suggesting that either nucleophilic attack of the exogenous PPh_2 ion is required to produce an sp^3C–P bond and/or substitution of the iminophosphine moiety by PPh_2 is necessary to form the $[PdL^C(\kappa\text{-}PPh_2)_2]^-$ intermediate, which then undergoes reductive elimination. The results of the experiments also show that intramolecular reductive elimination is unlikely for neutral Pd(II) intermediates with terminal PPh_2 ligands cis to sp^3C–Pd bonds at 75–80 °C in coordinating and non-coordinating solvents.

The iminophosphine formed as a result of the reductive elimination step can exist in the reaction mixture as a free ligand or be coordinated to Pd(0) or Pd(II) to form various complexes. Two different types of Pd(II) complexes with *N,P* ligands, **80** and **89**, were isolated in our study. It is noteworthy that Pd(0) complexes with *N,P* ligands have been reported.[30, 108-117] For example, Pd(0) complexes with *N,P* ligands **42** and **74** were studied by the van Koten group.[114] Both complexes Pd(**42**)$_3$ and Pd(**74**)$_3$ have three ligands coordinated to the metal through phosphorus atoms.

II.1.5. Conclusions

A general procedure for the formation of sp^2C–P and sp^3C–P bonds using reactions of dimeric dichloro-bridged CPCs with inexpensive $HPPh_2$ has been developed. The scope of complexes that can be used in the reaction include five- and six-membered *C,N*, *C,S* and

C,P palladacycles having either an sp^2 or and sp^3C–Pd bond. Achiral or enantiopure products with an sp^3C–PPh_2 bond, including amino- (**74**), quinolyl- **(82**), imino- (**78**), oximophosphines (**87** and **49**), and a diphosphine monoxide (**84**), were obtained in 30–65% yield, which is comparable to yields reported for preparation of these or similar *P*-containing bidentate ligands by other methods. Reactions in toluene involving CPCs derived from 2-*tert*-butyl-4,4-dimethyl-2-oxazoline and D-camphor methyloxime provided unique stable Pd(II) terminal phosphido complexes **80** and **89**. $^{31}P\{^1H\}$ NMR monitoring of reaction mixtures of $HPPh_2$ and sp^3C–Pd CPC **77** suggests that the anionic Pd(II) complex $[PdL^C(\kappa\text{-}PPh_2)_2]^-$, previously implicated in reactions of $LiPPh_2$ with CPCs, is likely to be a key intermediate undergoing reductive elimination to form a C–P bond. This method offers an approach to the regioselective introduction of PR_2 (where $R \neq Ph$) to ligands capable of cyclopalladation, whereas previous methods involving $MPPh_2$ are limited by the commercial availability of metal phosphides and their inconvenient solubility and storage.

II.2. Reactions of Cyclopalladated Complexes with HPR_2

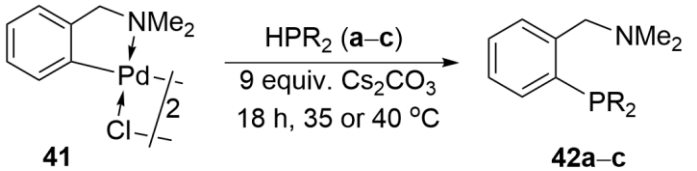
II.2.1. Background

Most recent approaches to Pd-mediated C–PR_2 bond formation use $HPPh_2$ as a model phosphine, as well as $HPAr_2$ with electron-withdrawing or -donating Ar groups. However, secondary phosphines with bulky or non-equivalent substituents have been neglected with the exception of Song and coworkers who have reported a Pd-catalyzed hydrophosphination with HP*i*-PrPh to obtain *N,P* ligand **7c** (Scheme 3). Modifying the bulk of tertiary phosphine substituents as well as introducing *P*-chirality is likely to have a pronounced effect on reactions utilizing them as organocatalysts or ancillary ligands of

metal catalysts.[118] Thus the electronic and steric factors of the starting secondary phosphines HPR_2 [R = *p*-$MeOC_6H_4$, *p*-$CF_3C_6H_4$, mesityl (Mes), and 1-adamantyl (Ad)] on reactions with model CPCs were investigated. HP*t*-BuPh was also reacted to assess the stereoselectivity of the C–P bond formation. Additionally, conditions were found for the synthesis of (i) uncommon mononuclear complexes with secondary phosphines as ancillary ligands, $L^CPdCl(HPR_2)$, and (ii) rare dinuclear complexes of type $L^CPd(\mu\text{-}Cl)(\mu\text{-}PR_2)PdL^C$, where L^C is a cyclopalladated ligand.

II.2.2. Reactions of CPCs with Electron-Deficient and -Rich Phosphines

It was previously reported that the dinuclear chloro-bridged *C,N* CPC **41** derived from *N,N*-dimethylbenzylamine was reacted with 4.5 equivalents of $HPPh_2$ (**a**) at 40 °C in toluene in the presence of 9 equivalents of Cs_2CO_3 to produce aminophosphine **42a** in 77% yield.[119] Under the same conditions, phosphination of CPC **41** with $HP(p\text{-}MeOC_6H_4)_2$, which has the electron-donating group compared to $HPPh_2$, yielded aminophosphine **42b** in 27% yield (Scheme 28 and Table 7, entry 2). By applying a significant excess of the phosphine, 9 equivalents, the yield of the phosphination product **42b** increased to 59%. Replacing toluene with more polar CH_2Cl_2 resulted in 61% yield of **42b**.



41 **42a–c**

R = Ph (**a**), *p*-$MeOC_6H_4$ (**b**) and *p*-$CF_3C_6H_4$(**c**)

Scheme 28. Reaction of CPC **41** with HPR_2.

Table 7. Conditions used in the reactions of CPC **41** with HPR_2.

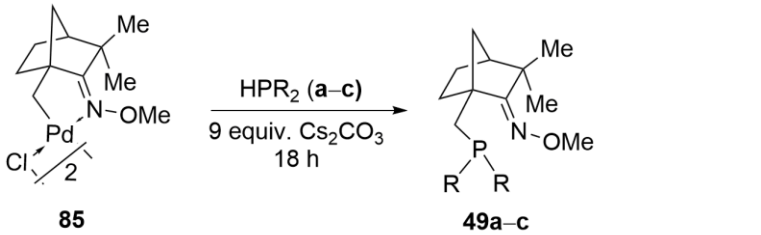
Entry	R	Solvent	Temp. (°C)	**1**:$HPAr_2$ Molar Ratio	Yield of **42** (%)
1[119]	Ph (**a**)	PhMe	40	1:4.5	77
2	*p*-$MeOC_6H_4$ (**b**)	PhMe	40	1:4.5	27
3	*p*-$MeOC_6H_4$ (**b**)	PhMe	40	1:9	59
3	*p*-$MeOC_6H_4$ (**b**)	CH_2Cl_2	35	1:9	61
4	*p*-$CF_3C_6H_4$ (**c**)	PhMe	40	1:4.5	56
5	*p*-$CF_3C_6H_4$ (**c**)	PhMe	40	1:9	traces*
6	*p*-$CF_3C_6H_4$ (**c**)	CH_2Cl_2	35	1:9	38

*29% of $L^CPd(\mu\text{-}Cl)(\mu\text{-}PR_2)PdL^C$ was isolated.

Using the standard conditions (PhMe, 40 °C, 18 h, 1:4.5 molar ratio), the reaction of CPC **41** with the phosphine having electron-withdrawing substituents, HP(*p*-$CF_3C_6H_4)_2$, provided the *N*,*P* ligand **42c** in 56% yield (entry 4). Increasing the number of equivalents of the starting phosphine led to a lower product yield (entry 5). In comparison to more electron-rich phosphines, the use of HP(*p*-$CF_3C_6H_4)_2$ has been reported in C–Pd to C–P bond transformations only once. In the asymmetric Pd-catalyzed synthesis of QUINAP derivatives from corresponding bromides, Bhat reported that reactions of HP(*p*-$CF_3C_6H_4)_2$ required longer reactions times to achieve full conversion of the starting material compared to the analogous transformations with $HPPh_2$ and HP(*p*-$CH_3C_6H_4)_2$.[46] Presumably, those reactions proceeded via the formation of cyclopalladated complexes followed by reductive elimination.[47] According to the data presented by Hartwig in his review and the conclusions made therein, the rate of the C–P bond forming reductive elimination step is expected to be higher for more electron-rich phosphido groups in Pd(II) complexes.[120]

To compare the $HPAr_2$ reactions involving CPC **41**, which has an sp^2C–Pd bond, analogous experiments with the L-(–)-fenchone-derived CPC **85** were performed. This complex was chosen because (i) it is readily available,[58] (ii) it has an sp^3C–Pd bond, (iii) it

is enantiopure (*vide infra*), and (iv) its phosphination with 9 equivalents $HPPh_2$ provided a rather high yield (65%) of *N*,*P* ligand **49a**.[119] Reactions of $HP(p\text{-}RC_6H_4)_2$ (R = OMe or CF_3) with complex **3** in PhMe and CH_2Cl_2 furnished moderate yields of aminophosphines **49b**,**c** (Scheme 29 and Table 8, entries 1–7).



85 **49a–c**

R = Ph (**a**), *p*-$MeOC_6H_4$ (**b**) and *p*-$CF_3OC_6H_4$ (**c**)

Scheme 29. Reaction between CPC **85** and HPR_2 (**a**–**c**).

Table 8. Conditions used for reactions of CPC **85** with HPR_2.

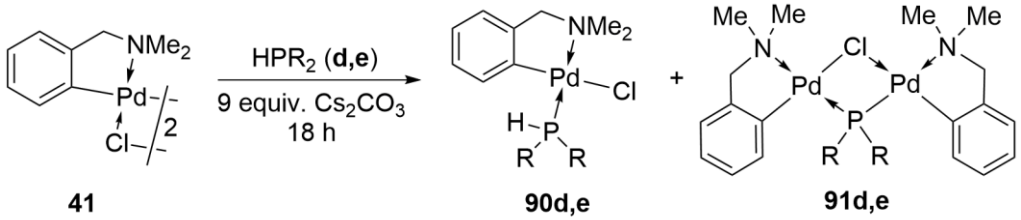
Entry	R	Solvent	Temp (°C)	**3**:$HPAr_2$ Molar Ratio	Yield of **49** (%)
1[119]	Ph (**a**)	CH_2Cl_2	35	1:9	65
2	*p*-$MeOC_6H_4$ (**b**)	PhMe	40	1:4.5	30
3	*p*-$MeOC_6H_4$ (**b**)	PhMe	40	1:9	44
4	*p*-$MeOC_6H_4$ (**b**)	CH_2Cl_2	35	1:9	36
5	*p*-$CF_3C_6H_4$ (**c**)	PhMe	40	1:4.5	0
6	*p*-$CF_3C_6H_4$ (**c**)	PhMe	40	1:9	25
7	*p*-$CF_3C_6H_4$ (**c**)	CH_2Cl_2	35	1:9	53

Similar to the results involving CPC **41** with an sp^2C–Pd bond, the reaction of the fenchone-derived complex **85** with $HPPh_2$ gave significantly higher yields of *N*,*P* ligand **49a** than phosphinations with either $HP(p\text{-}MeOC_6H_4)_2$ or $HP(p\text{-}CF_3C_6H_4)_2$. This suggests that the electron density of the phosphine, regardless of the hybridization of the chelating carbon in the CPC, has an important influence on product formation.

II.2.3. Reactions of CPCs with Bulky Secondary Phosphines

After evaluating the electronic effect of $HPAr_2$, the bulkiness of the phosphine was considered in reactions of complexes **41** and **85** with commercially available $HPMes_2$ (**d**)

and $HPAd_2$ (**e**). The experiments using CPC **41** with 4.5 equivalents of $HPMes_2$ in PhMe and with 9 equivalents of the same phosphine in CH_2Cl_2 did not result in the desired C–P bond formation. Instead, traces of the mononuclear complex **90d** were obtained as well as a small amount of the dinuclear complex **91d** (Scheme 30; Table 9, entries 1 and 2). These two complexes, **91d** and **90d**, were isolated in excellent yields using 1 and 2 equivalents of $HPMes_2$, respectively (entries 3 and 4). All attempts (i.e., longer periods of time up to 96 h and higher temperatures up to 80 °C in PhMe) to obtain the aminophosphine product were unsuccessful.



Scheme 30. Reaction between CPC **41** and bulky HPR_2.

Table 9. Conditions used in the reaction shown in Scheme 30.

Entry	R	Solvent	Temp (°C)	Molar Ratio	Yield of **90** (%)	Yield of **91** (%)
1	Mes (**d**)	PhMe	40	1:4.5	Traces	10
2	Mes (**d**)	CH_2Cl_2	35	1:9	Traces	12
3	Mes (**d**)	PhMe	40	1:1	0	98
4*	Mes (**d**)	CH_2Cl_2	Rt	1:2	90	0
5	Ad (**e**)	PhMe	40	1:4.5	75	0
6	Ad (**e**)	CH_2Cl_2	35	1:9	79	0
7*	Ad (**e**)	CH_2Cl_2	Rt	1:2	90	0

*Reactions were stopped after 30 min. and no base was used.

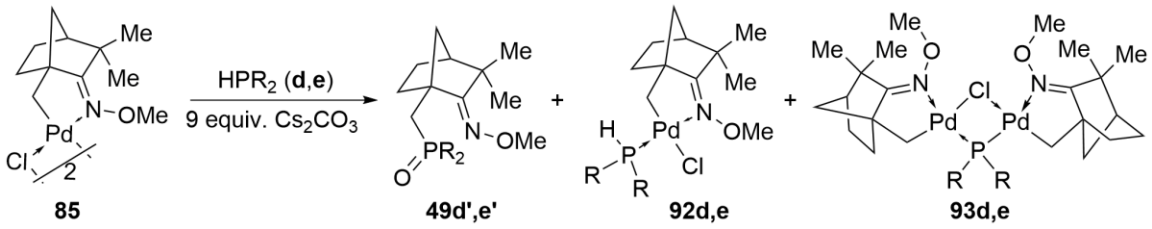
Reactions of CPC **41** with another phosphine with bulky substituents, $HPAd_2$, gave only the corresponding $HPAd_2$ adduct **90e** under all conditions tried, including those extending for 96 h and performed at higher temperature (80 °C in PhMe; see also entries 5

and 6 in Table 9). Neither the targeted aminophosphine ligand nor the monophosphido-bridged complex **91e** were formed in those experiments. Moreover, the ^{1}H NMR spectrum of the reaction mixture with a 1:1 ratio of CPC **41** and $HPAd_2$ (the best ratio for the preparation of complexes of the type $L^{C}Pd(\mu\text{-}Cl)(\mu\text{-}PR_2)PdL^{C}$)[55] contained only signals of the starting complex **41** and adduct **90e**.

It has been suggested that complexes with more hindered ancillary ligands may undergo reductive elimination faster than those with less bulky ancillary ligands.[120] This was explained by "a relief in steric congestion upon generation of the free organic product and a resulting metal center with a reduced coordination number."[120] If so, it is possible to predict that increasing the size of the PR_2 ligand in the intermediate undergoing reductive elimination will facilitate C–P bond formation for the same reasons. Previously, complexes of the type $L^{C}Pd(\mu\text{-}PR_2)(\mu\text{-}Cl)PdL^{C}$ along with $[L^{C}Pd(PR_2)_2]^{-}$ were identified as possible intermediates in phosphination of cyclopalladated ligands.[55, 119] In the case of bulky phosphines, the formation of the latter intermediate is problematic because two hindered PR_2 ligands are unlikely to be in the cis position required for this complex. The fact that the compound $L^{C}Pd(\mu\text{-}PR_2)(\mu\text{-}Cl)PdL^{C}$ **91d** was isolated only using $HPMes_2$ and no targeted aminophosphine was obtained with either of two tested bulky phosphines, indirectly supports our hypothesis[55, 119] that aminophosphines are formed as a result of the reductive elimination from the diphosphido complexes $[L^{C}Pd(PR_2)_2]^{-}$.

Reactivity of CPC **85** with an sp^3C–Pd bond toward the bulky phosphines was somewhat different compared to that of CPC **41** with an sp^2C–Pd bond (Scheme 31 and Table 10). The desired phosphination product **49d´** with the oxidized $PMes_2$ group was obtained after 18 h in 7% yield using 9 equivalents of $HPMes_2$ (entry 2). The increase in

the reaction time to 96 h resulted in 32% yield of **49d´** (entry 3). All attempts to synthesize the analogous compound **49e** with the PAd_2 moiety were unsuccessful. Complexes **92d**,**e** and/or **93d,e** were major products of the reactions performed using all other conditions tested (Table 10). Compounds **92d,e** were obtained in high yield using 2 equivalents of HPR_2 (R = Mes or Ad) in CH_2Cl_2 (entries 4 and 7). The best yields of the monophosphido-bridged complexes **93d,e** were achieved in the reactions using a 1:1 ratio of the reagents in CH_2Cl_2 at 35 ºC and in PhMe at 80 ºC, respectively (entries 3 and 8).



Scheme 31. Reaction between CPC **85** and bulky HPR_2 (R = Mes or Ad).

Table 10. Conditions used for reaction in Scheme 31.

Entry	R	Solvent	Temp (°C)	Molar Ratio	**49'** (%)	**92** (%)	**93** (%)
1	R = Mes (**d**)	PhMe	40	1:4.5	0	traces	8
2	R = Mes (**d**)	CH_2Cl_2	35	1:9	7	0	0
3*	R = Mes (**d**)	CH_2Cl_2	35	1:9	32	0	0
4	R = Mes (**d**)	CH_2Cl_2	35	1:1	0	0	69
5†	R = Mes (**d**)	CH_2Cl_2	Rt	1:2	0	81	0
6	R = Ad (**e**)	PhMe	40	1:4.5	0	77	0
7	R = Ad (**e**)	CH_2Cl_2	35	1:9	0	81	0
8*	R = Ad (**e**)	CH_2Cl_2	35	1:9	0	31	45
9†	R = Ad (**e**)	CH_2Cl_2	Rt	1:2	0	86	0
10	R = Ad (**e**)	PhMe	80	1:1	0	19	66

* Reaction time: 96 h.
† Reactions were stopped after 30 minutes and no base was used.

It is noteworthy that, contrary to a large number of studies on mononuclear CPCs with PPh_3 or other tertiary phosphines ligands, there are just five reports describing their analogs with secondary phosphines.[121-125] All of them are of the *C,N*-type and contain an

sp^2C–Pd bond in either a five- or six-membered palladacycle. Mononuclear complexes derived from *ortho*-palladated *N,N*-dimethyl-2-aminobiphenyl and HPR_2 with bulky substituents (R = Nor, *t*-Bu, or Cy) proved to be excellent catalysts in Heck and other C–C and C–N coupling reactions.[122]

Mononuclear complexes **90d,e** and **92d,e** with $HPMes_2$ and $HPAd_2$ as ancillary ligands are expected to have the trans-*P,N* geometry as all other known phosphine adducts of *C,N* CPCs. ^{1}H, ^{13}C and ^{31}P NMR spectra of compound **92e** revealed that this CPC exists in solution as two isomers in a ratio of 4:1. These two isomers for **92e** can be either cis/trans-*N,P* adducts or rotamers due to restricted rotation around the Pd–P bond. The ^{1}H, ^{13}C and ^{31}P NMR signals of two isomers differ insignificantly, except for the signals of the hydrogen bonded to the phosphorus atom, which appear as doublets at δ 3.36 and 4.06 ppm with $^1J_{HP}$ = 339 and 359, respectively. These data suggest that the two isomers have a similar geometry; however, the P–H fragments in these molecules have rather different chemical environments. For five closely related PPh_3 adducts of five-membered sp^3C,sp^2N CPCs with trans-*N,P* geometry, the ^{1}H NMR triplets ($^3J_{HP}$ = 7.2–9 Hz) assigned to one of the two diastereotopic hydrogens of the Pd–CH_2 fragment are significantly shifted upfield (δ 0.56–1.09 ppm) compared to the spectra of the corresponding dichloro-bridged dimers (δ 1.86–2.18 ppm).[58, 59, 126, 127] In the ^{1}H NMR spectrum of **92e**, one of the hydrogens of the CH_2Pd group in the major isomer provides a triplet at δ 1.15. NOE interactions were observed between this signal and the corresponding HP doublet centered at δ 3.36 ppm. The result of the NOE experiment as well as the similarity in the CH^APd chemical shift and $^3J_{HP}$ coupling constant values for the major isomer of **92e** with closely related complexes with the trans-*N,P* geometry strongly suggest that it has the same stereochemistry.

Unfortunately, the ^{1}H NMR signals of the $PdCH_2$ moiety in the minor isomer were overlapped with other signals, and NOE experiments could not be used reliably in this case. There are a few arguments to suggests the trans-*N*,*P* geometry not only for the major but also for the minor isomer of **92e**. First, the ^{1}H NMR chemical shifts of the NOMe group in both isomers differ by 0.01 ppm indicating their very similar chemical environment. One can expect that the chemical shift of the NOMe group near two bulky adamantyl substituents in the cis-*N*,*P* isomer would be different. Secondly, the value of $^{2}J_{CP}$ constant, 4 Hz, for the $PdCH_2$ group of the minor isomer is similar to the values of the $^{2}J_{CP}$ constants reported earlier[58, 59, 93, 126, 127] (0–3 Hz) and in this dissertation (0−4 Hz) for mononuclear CPCs with the cis position of the chelating C (either sp^2 or sp^3) and P atoms. For comparison, the value for the $^{2}J_{CP}$ constant reported for the $PdCH_2$ group in the complex of the type $L^{C}Pd(\mu\text{-}PPh_2)_2PdL^{C}$ was 55.1 Hz.[57] Finally, the trans position of a phosphine ligand relative to a donor carbon atom in Pd(II) complexes is unlikely due the transphobia effect[84, 128, 129] and, to the best of our knowledge, there is only example of a mononuclear CPC having a phosphine ancillary ligand in trans-*C*,*P* geometry, but the ^{13}C NMR data was not given.[31] By contrast, a mononuclear Pd(II) complex with a bulky *N*-heterocyclic carbene ligand trans to $HPAd_2$, $(NHC)PdCl_2(HPAd_2)$, has been reported, with the $^{2}J_{CP}$ constant listed as 189.2 Hz. For similar complexes with tertiary phosphines in place of $HPAd_2$, this $^{2}J_{CP}$ constant was 181.9–199.2 Hz.[130]

Assuming that both isomers of **92e** have the trans position of $HPAd_2$ relative to the N atom of the fenchone-derived ligand, the presence of two sets of signals with similar chemical shift values in ^{1}H, ^{13}C and ^{31}P NMR spectra of **92e** can be explained by the existence of two rotamers due to restricted rotation around the P–Pd bond. This restricted

rotation has been reported for mononuclear CPCs with the secondary phosphine HPBnPh,[124] and with tertiary phosphines P*t*-BuPh(4-BrC_6H_4),[131] PBn*i*-PrPh,[132] PBnCyPh,[124] and PBn_2Ph;[124] however, in all these cases only one set of signals was present in the ^{1}H NMR spectra. The existence of two rotamers of complex **92e** in solution is not surprising considering the larger size of the 1-adamantyl group compared to substituents in other phosphine ligands for which restricted rotation was observed. It is also noteworthy that complex **92e** appears to be the first cyclopalladated complex with a phosphine as an ancillary ligand for which two rotamers have been reported.

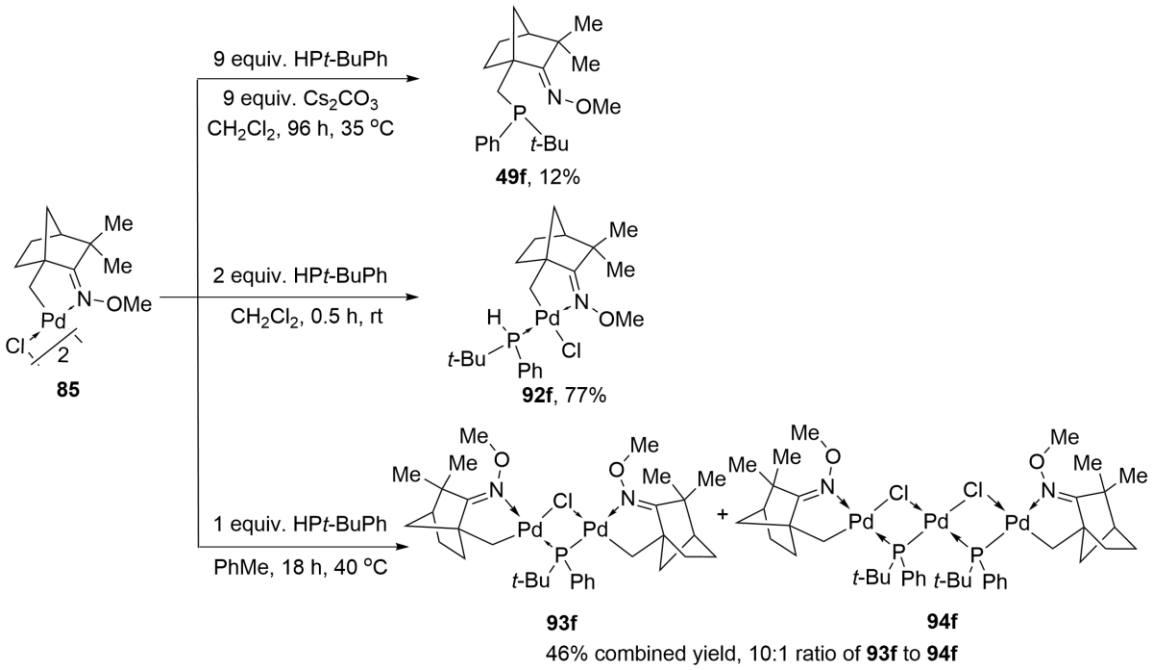
Complexes of the type $L^CPd(\mu\text{-}Cl)(\mu\text{-}PR_2)PdL^C$ have been previously isolated in the reactions of CPCs with $LiPPh_2$,[53] $KPPh_2$,[55, 57] and $HPPh_2$.[119] X-ray structural data for one of the *C,N* complexes of this kind were reported by Dunina et al.*[133]* confirming the cis position of two cyclopalladated ligands (L^C) and the trans position of the PPh_2 group relative to the N atoms in both ligands L^C. Similarly to all known CPCs of this kind, NMR spectra of complexes **91d** and **93d,e** have one set of signals for the chelating moieties. This confirms their equivalence, which is possible only for complexes $L^CPd(\mu\text{-}Cl)(\mu\text{-}PR_2)PdL^C$ having two cyclopalladated ligands in the cis position. Furthermore, the PR_2 bridging unit is expected to be cis to the chelating carbon atoms according to the transphobia effect.[84, 128, 129]

*II.2.4. Reactions of CPCs with the Chiral Phosphine HP*t*-BuPh*

Aminophosphines of type **42** and **49** as well as the new Pd(II) complexes obtained in this study are potential catalysts in various transformations including C–C coupling and hydrogenation.[1, 6, 122] Optically active aminophosphines and other bidentate *N,P* ligands with a chelating *P*-chiral center are expected to have a greater influence on the

stereoselectivity of transition-metal-catalyzed reactions. For this reason, reactions of three enantiopure CPCs and commercially available racemic HP*t*-BuPh were explored with the goal of synthesizing chiral phosphines having both *C*- and *P*-stereocenters.

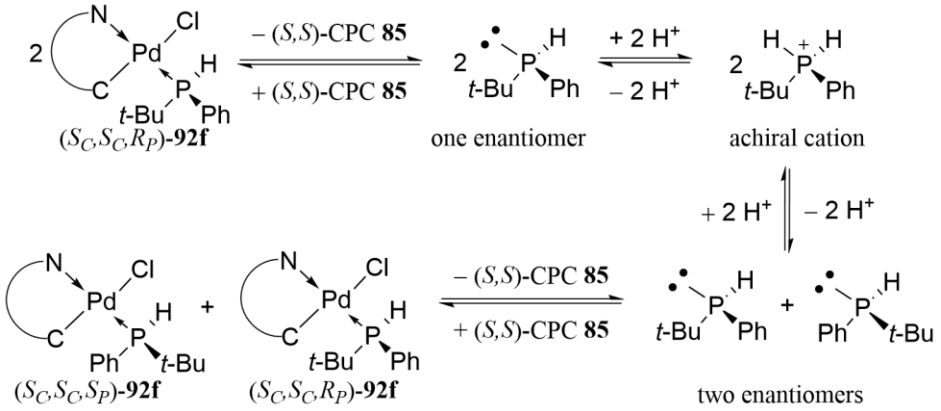
In the reactions of the optically active CPC **85** with rather bulky HP*t*-BuPh (Scheme 32), conditions determined to be the best for the synthesis of *N,P* ligand **49d'** with the large $PMes_2$ substituent (Table 10, entry 3) were used. The ^{31}P NMR spectrum of the reaction mixture after 96 h showed a strong signal at –18.6 ppm with negligible surrounding peaks. After preparative TLC on SiO_2, 12% of one pure diastereomer of **49f** was isolated. The second diastereomer was either not formed or not recovered from the TLC plate. The stereochemical purity of the isolated sample of *N,P* ligand **49f** was supported by the presence of one set of signals in ^{1}H, ^{13}C, and ^{31}P NMR spectra. The ^{31}P NMR spectrum of compound **49f** stored at rt in toluene-d_8 after 48 h exhibited a single peak, suggesting that racemization of the *P*-chiral center did not take place. It is noteworthy that attempts to use a shorter reaction time or toluene instead of CH_2Cl_2 did not result in the formation of **49f**.



Scheme 32. Preparation of **49f**, **92f**, and a 10:1 mixture of **93f** and **94f**.

The synthesis of complexes **92f** and **93f** from CPC **85** was also investigated due to their potential in catalysis. Compound **92f** was isolated as a 1:1 mixture of two diastereomers in a combined yield of 77% using a 1:2 molar ratio of CPC **85** and HP*t*-BuPh at rt (Scheme 32). To investigate a possibility of diastereoselective complexation of the racemic phosphine, 4 equivalents of HP*t*-BuPh were reacted with the dimeric CPC **85** at –78 °C for 30 minutes in CH_2Cl_2. Two diastereomers of **92f** were isolated using preparative TLC in a 5:4 ratio in a combined yield of 71%. Attempts to separate the diastereomers by recrystallization were unsuccessful because of the high solubility of the complex in organic solvents. Separation of the diastereomers using TLC on silica gel was also unsuccessful with several different eluents. However, when the 1:4 reaction mixture of CPC **85** and HP*t*-BuPh in toluene-d_8 was monitored at rt, a single set of signals was observed in the ^{31}P NMR spectra immediately after mixing and one hour later. These data suggest that the formation

of adduct **92f** in toluene is highly diastereoselective. However, on silica gel or in the presence of acidic impurities (such as traces of HCl in halogenated solvents), epimerization of complex **92f** take place. The epimerization is promoted by protonation of the free phosphine, which results in the formation of the achiral phosphonium cation H_2t-BuPhP$^+$ (Scheme 33).



Scheme 33. Epimerization of complex (S_C,S_C,R_P)-**92f** on silica gel or in the presence of traces of HCl.

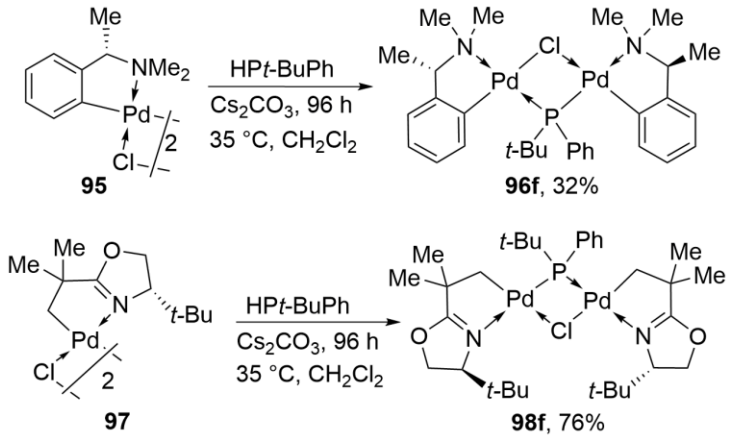
For comparison, Dunina et al. described a similar reaction of an enantiopure CPC derived from *N*-isopropyl-*α*-methylbenzylamine with 4 equivalents of P*t*-BuMePh at rt.[134] A single diastereomer of the resultant complex with the tertiary phosphine was isolated after one recrystallization. Albert et al. described preparation of diastereomeric mixtures obtained by reacting optically active dimeric CPCs with 2 equivalents of racemic secondary phosphines, HPMePh and HPBzPh.[125] The authors were able to separate two diastereomers using column chromatography.

Complex **93f** was obtained after stirring with 1 equivalents of HP*t*-BuPh in PhMe at 40 °C for 18 h (Scheme 32). Due to the transphobia effect,[83, 84, 128] the major isomer is most likely to have the cis position of two cyclopalladated ligands with the phosphido

moiety trans to the *N* atoms. Due to the presence of two different substituents in the phosphido ligand and two chiral centers in the fenchone moiety, the two cyclopalladated ligands are non-equivalent. As a result, ^{1}H and ^{13}C NMR spectra of **93f** have two sets of signals for these ligands.

NMR spectra of all fractions of compound **93f** contained one more set of signals in the amount of ca. 10%. At first, it was concluded that it was a minor isomer because the chemical shifts of the second compound present in the mixture were very similar to those of **93f**. That minor compound had only one set of signals in the ^{1}H, ^{13}C and ^{31}P NMR spectra; therefore, it could not have the trans position of two fenchone moieties since the cyclopalladated ligands would be non-equivalent. It is likely that the minor compound accompanying complex **93f** is not its isomer but rather its trinuclear analog, $L^{C}Pd(\mu\text{-Cl})(\mu\text{-P}t\text{-BuPh})Pd(\mu\text{-P}t\text{-BuPh})PdL^{C}$ (**94f**, see Scheme 32). One example of a trinuclear complex of this type was reported previously, isolated from the reaction of a camphor-derived CPC with $KPPh_2$.[57]

In an attempt to expand the number of the *N*,*P* ligands with chiral *C* and *P* centers, two other enantiopure CPCs, **95** and **97**, were reacted with HP*t*-BuPh (Scheme 34). Even after 96 h at 35 °C, both complexes gave only monophosphido-bridged complexes **96f** and **98f** without traces of the desired *N*,*P* ligands. Complexes **93f**, **96f** and **98f** were enantiopure and did not require separation of diastereomers. As expected, they provide only one signal in $^{31}P\{^{1}H\}$ NMR spectra; however, some signals of the cyclopalladated ligands are doubled due to the presence of non-equivalent substituents in the bridging phosphido unit.



Scheme 34. Reactions of CPCs **95** and **97** with HP*t*-BuPh.

II.2.5. ^{31}P NMR Spectral Data for Synthesized Compounds

^{31}P NMR spectroscopy is a useful tool for identifying *P*-containing compounds in general and, specifically, products of the reactions described in the present study. As shown in Table 11, *N,P* ligands, mononuclear complexes with a secondary phosphine as an ancillary ligand, the corresponding oxides of *N,P* ligands, and monophosphido-bridged CPCs have specific chemical shift regions downfield (listed in order) from the parent secondary phosphines. Three free phosphines $HPAr_2$ (Ar = Ph, *p*-$MeOC_6H_4$, and *p*-$CH_3C_6H_4$) provided signals in the narrow range of δ –54.5 to –59.5 ppm. Introduction of two bulky mesityl groups significantly shifted the signal of the secondary phosphine upfield to δ –108.1 ppm. In contrast, $HPAd_2$ with bulky but aliphatic substituents underwent resonance at δ +2.7 ppm. Arylation of $HPAr_2$ led to downfield shifts, Δ +25.5 ± 0.9 ppm, from the signals of the parent phosphines (see data for **42a–c**) compared to Δ = +19.0 ± 1.4 ppm for alkylations (see data for **49a–c**). Signals of phosphine oxides **42a´** and **49a´** moved downfield by Δ +46.9 and +51.9 ppm from those of their corresponding tertiary phosphines.

Table 11. $^{31}P\{^{1}H\}$ NMR chemical shifts of the compounds used or synthesized in this study.

PR^1R^2	Compound Type and Its Chemical Shift in $CDCl_3$, ppm				
	HPR^1R^2	*N,P* ligand	*N,P* oxide ligand	$L^CPdCl(HPR_2)$	$L^CPd(\mu\text{-}Cl,\mu\text{-}PR_2)PdL^C$
$R^1=R^2=Ph$	–54.5 –55.4*	**42a**: –30.3[53] **49a**: –36.9,[57] –23.2[57,*]	**42a'**: +16.6[53] **49a'**: +15.0[57]		**91a:** +25.1[53], +30.3[§] **93a**: +2.2,[57] +18.0[‡]
$R^1=R^2=$ *p*-$MeOC_6H_4$	–59.8	**42b**: –33.5 **49b**: –41.5			
$R^1=R^2=$ *p*-$CF_3C_6H_4$	–55.9	**42c**: –30.2 **49c**: –35.5			**91c**: +19.9
$R^1=R^2=Mes$	–108.1		**49d'**: –45.7	**90d:** –47.6 **92d**: –54.6	**91d**: –12.1 **93d**: –44.7
$R^1=R^2=Ad$	+2.7			**90e**: +71.3 **92e**:[†] +49.5, +51.7	**93e**: +70.5
$R^1=$*t*-Bu $R^2=Ph$	–20.4 –24.7*	**49f**: –18.6, –23.8*		**92f**:[†] +27.3, +27.4	**93f**: +33.7 **96f**: +45.7 **98f**: +32.5

* Toluene-d_8 was used as the solvent.
[†] Data are for two diastereomers.
[§] thf-d_8 was used as the solvent.
[‡] C_6D_6 was used as the solvent.

Complexation of HPR_2 and HP*t*-BuPh to form $L^CPdCl(HPR_2)$ was accompanied by signal shifts to lower fields by Δ +60.5 and +68.5 ppm (**90d,e** with an sp^2C–Pd bond) and Δ +46.8 to +49.0 ppm (**92d–f** with an sp^3C–Pd bond). For comparison, the reported chemical shifts of the same CPCs (**90** and **92**) with tertiary phosphine PPh_3 instead of HPR_2 are δ +27.3 ppm[53] (Δ +33.3 ppm relative to the signal of free PPh_3) and δ +20.3 ppm[58] (Δ +26.3).

Complexes of the type $L^CPd(\mu\text{-}Cl,\mu\text{-}PR_2)PdL^C$ had signals the farthest downfield from the corresponding phosphine in comparison to other related compounds. The data for sp^2C–Pd CPCs **91a,c,d** and **96f** show that the downfield shift value significantly depended on the substituents of the secondary phosphine HPR^1R^2, with $R^1 = R^2$ = Mes giving the

greatest shift followed by $R^1 = R^2$ = Ph, $R^1 = R^2$ = *p*-$CF_3C_6H_4$, and R^1 = *t*-Bu, R^2 = Ph (Δ +96.0, 79.6, 75.8, and 66.1 ppm for **91d,a,c** and **96f**, respectively). ^{31}P NMR signals of the closely related complexes **93a,d–f** and **98f** with an *sp*^{3}*C,N* ligand also moved downfield by Δ +52.9 to +67.8 ppm with the highest value for the PAd_2 derivative **93e**.

The solvent used for recording ^{31}P NMR spectra had a noticeable effect on the chemical shift of phosphines and complexes **49a,f** and **93a**. The use of C_6D_6 instead of $CDCl_3$ caused the upfield shift of Δ –4.3 and –5.5 ppm on the chemical shifts of free HP*t*-BuPh and functionalized phosphine **49f**. Interestingly, the signal of complex **93a** in another aromatic solvent, toluene-d_8, shifted to the opposite direction (Δ +15.8). A similar downfield shift (Δ +13.2) was observed in the ^{31}P NMR spectrum of a related CPC by replacing $CDCl_3$ with C_6D_6.[119] A smaller downfield shift, Δ +5.2 ppm, was reported for the signal of complex **91a** in less polar but coordinating thf-d_8.[53]

*II.2.6. X-Ray Crystallographic Analysis of Complex **92d***

The mononuclear structure of complex **92d** and its trans-*N,P* geometry were confirmed by X-ray crystallographic study. The molecular structure of the complex and the numbering scheme are shown in Figure 5. Selected bond lengths and bond angles are shown in Tables 12 and 13. The data obtained for complex **92d** are compared to those reported for related complexes **G**–**L** (Chart 1).[58, 126, 135-137]

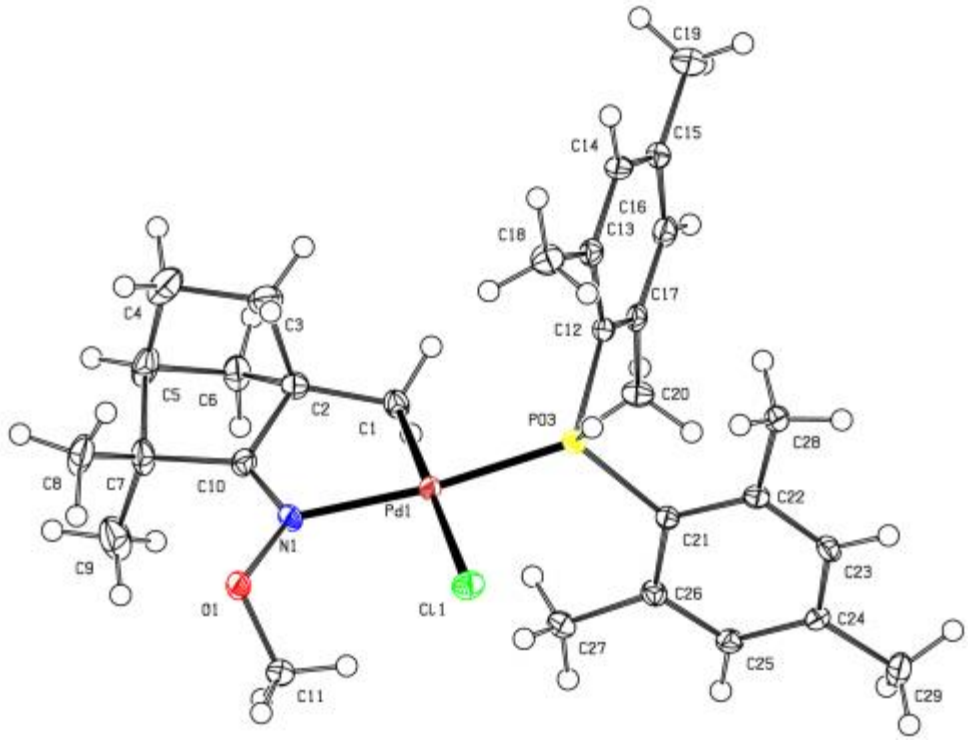
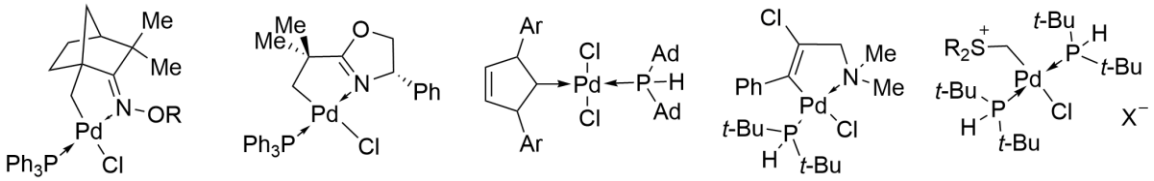


Figure 5. ORTEP drawing of the molecular structure of complex **92d**. Thermal ellipsoids are shown at the 50% probability level.

Table 12. Selected bond lengths (Å) for complex **92d** and their comparison with related compounds **G**,[58] **H**,[58] **I**·0.25CH_2Cl_2,[126] **J**,[135] **K**,[136] and **L**.[137]

Bond Type	**92d**	**G**	**H**	**I**	**J**	**K**	**L**
Pd(1)−C(1)	2.055	2.051(4)	2.063(5)	2.051	2.044	2.050(3)	2.064
Pd(1)−P(3)	2.227	2.222(10)	2.2250(12)	2.2563	2.327	2.2722(8)	2.3285*
Pd(1)−N(1)	2.103	2.064(3)	2.115(4)	2.072	n/a	2.186(3)	n/a
Pd(1)−Cl(1)	2.409	2.4019(9)	2.3822(11)	2.421	2.3035*	2.4013(9)	2.359
N(1)−C(3)	1.269	1.273(5)	1.273(6)	n/a	n/a	n/a	n/a
N(1)−O(1)	1.415	1.391(4)	1.4141(5)	n/a	n/a	n/a	n/a
C(2)−C(1)	1.520	1.526(5)	1.517(6)	1.5465	n/a	n/a	n/a
C(2)−C(10)	1.499	1.502(5)	1.500(6)	1.4898	n/a	n/a	n/a
P(3)−H	1.270	n/a	n/a	n/a	1.000	1.278	1.3695*

* Average of two distances.



G: R = H
H: R = Me

I

J: Ar = 2,6-(*i*-Pr)$_2$C$_6$H$_3$

K

L: R = Et, X = PF_6

Chart 3. Examples of Pd(II) complexes with a known molecular structure, which have either an sp^3C,sp^2N palladacycle (**G**–**I**) or a secondary phosphine as a ligand (**J**–**L**).

Table 13. Selected bond angles (°) for complex **92d** and their comparison with related compounds **G**,[58] **H**,[58] and **I**·0.25CH_2Cl_2.[126]

Bond Type	**92d**	**G**	**H**	**I**
C(1)-Pd(1)-N(1)	80.60	81.43(14)	79.25(17)	79.57
C(1)-Pd(1)-P(3)	94.25	89.70(11)	90.25(13)	90.61
C(1)-C(2)-C(10)	112.17	112.0(3)	110.7(4)	105.21
C(2)-C(10)-N(1)	116.61	115.3(3)	117.3(4)	121.25
C(2)-C(1)-Pd(1)	107.49	106.2(3)	105.5(3)	110.71
C(10)-N(1)-Pd(1)	115.48	116.4(3)	112.9(3)	114.23
N(1)-Pd(1)-Cl(1)	99.05	87.18(9)	95.05(11)	90.55
P(3)-Pd(1)-Cl(1)	86.05	101.61(4)	95.31(4)	99.37
N(1)-Pd(1)-P(1)	173.79	171.11(9)	167.58(11)	169.68
C(1)-Pd(1)-Cl(1)	179.09	167.91(12)	174.23(13)	167.48

The Pd–X [X = C(1), P, N and Cl] bond lengths in **92d** are within the ranges reported for the related Pd(II) complexes **G**–**L** (Table 12). The bond lengths within the palladacycle in **92d** are similar to those reported for two other fenchone-derived CPCs **G** and **H**.

The value of the C(1)-Pd-N angle in the palladacycle of complex **92d** is a close match to those reported for compounds **G** and **H**. However, the C(1)-Pd-P and N-Pd-Cl angles in **92d** are 4.00−11.87° greater than those in complexes **G** and **H** (Table 13). As a consequence, the value of the P-Pd-Cl angle is unusually small at 86.05° compared to those in other mononuclear CPCs **G**–**I**, which also have an sp^3C and sp^2N donor atoms in the palladacycles. These observations can be explained by steric factors. In the crystal of

complex **92d**, the small hydrogen of the $HPMes_2$ ligand is closer to the Cl atom, while two bulky mesityl substituents are somewhat closer to the $C(1)H_2$ fragment of the palladacycle. These steric requirements make the C(1)-Pd-P angle larger and the P-Pd-Cl smaller compared to the corresponding angles in complexes **G**–**I**, which all have the PPh_3 ligand.

The palladium atom in complex **92d** has square-planar coordination with a slight distortion. The torsion angles Pd-N-C(1)-P, Pd-C(1)-P-Cl, Pd-P-Cl-N and Pd-Cl-N-C(1) have the same sign; therefore, the distortion can be described as pyramidal. The distortion from the ideal square-planar coordination in CPC **92d** is smaller than that in the closely related complexes **G** and **H** as the distance from the mean plane {PClC(1)N}to the metal in **92d** is 0.041 Å compared to 0.049 and 0.075 Å determined for **G** and **H**, respectively.[58] The angle between the planes {NPdC(1)} and {PPdCl} is equal to 3.6° in **92d** compared to 4.3 and 6.8° in **G** and **H**.

The palladacycle conformation in complex **92d** is a slightly twisted envelope with the Pd atom serving as the envelope flap. The sum of absolute values of intrachelate torsion angles in the palladacycle is 87.04° with the average angle value of 17.41°. This metallacycle is slightly less distorted than those in complexes **G**–**I**: the sum of absolute values of intrachelate torsion angles in the corresponding palladacycles is equal to 93.50, 123.24 and 97.56°.[58, 126]

II.2.7. Conclusions

Product formation in reactions of chloro-bridged dimeric CPCs with secondary phosphines is sensitive to the molar ratio of the reagents, base presence, solvent, time and temperature and provide either aminophosphines (or other *N,P* ligand), mononuclear HPR_2 adducts or monophosphido-bridged dimeric CPCs. Electronic factors of the aryl groups in

$HPAr_2$ appear to play little role on the selectivity of product formation; however, the *N,P* ligands were obtained in lower yields than in the analogous reactions involving $HPPh_2$. The application of bulky phosphines, i.e. $HPMes_2$, H*t*-BuPh and especially $HPAd_2$, in reactions with CPCs significantly decreases the probability of a C–PR_2 bond formation. Reaction of the enantiopure fenchone-derived CPC **85** with racemic HP*t*-BuPh afforded the desired *N,P* ligand **49f**, which was isolated as a single diastereomer in 12% yield. Using the same racemic phosphine, unique enantiopure mono-phosphido-bridged complexes **93f**, **96f** and **98f** were synthesized in good yields. Compound **92e** appears to be the first mononuclear cyclopalladated complex with a phosphine ancillary ligand for which two rotamers in solution have been observed.

II.3. Oxygenation of Cyclopalladated Ligands

II.3.1. Background

Transformations at the C–Pd bond of cyclopalladated complexes represent an attractive method for highly regioselective functionalization of organic compounds, but ligand modifications other than phosphination are of interest, including halogenation,[138-146] acetoxylation,[147-152] and others.[144, 153-158] These Pd-mediated transformations are gaining importance as a synthetic method, providing access to new organic and organometallic compounds not readily available by other methods. Furthermore, these reactions are great models for studying related Pd-catalyzed transformations involving substrates with chelating groups since many of them are thought to proceed through cyclopalladated intermediates.[152, 159-161] In this work, oxygenation of cyclopalladated ligands is the focus.

Oxygen insertion into the C–Pd bond of cyclopalladated complexes can be accomplished by any of the following reagents: *m*-chloroperoxybenzoic acid (*m*-CPBA)

(used alone[162-174] or with an iron(III) porphyrin catalyst[169]), other peroxy acids,[163] *tert*-BuOOH (used alone[33, 175-178] or with a catalyst[164, 165, 175-180]), hydrogen peroxide in the presence of an iron(III) porphyrin catalyst,[181] pentafluoroiodosylbenzene C_6F_5IO (alone,[169, 180] in a combination with *tert*-BuOOH,[169, 180] or in the presence of an iron(III) porphyrin catalyst[169, 180]), iodosylbenzene C_6H_5IO,[182] [di(benzoyloxy)iodo]benzene $PhI(O_2CPh)_2$,[183] and the molybdenum peroxide $MoO(O_2)_2 \cdot HMPA \cdot H_2O$ (HMPA = hexamethylphosphoric triamide).[138, 184] The mechanisms involved in these transformations appear to be different;[185] however, in all cases, the C–Pd bond is transformed into the C–O–Pd moiety.

It appears that *m*-CPBA is the most common and inexpensive oxidant used for metaloxylation of CPCs. However, in spite of the number of studies focused on reactions of CPCs with *m*-CPBA, only a few rather similar types of palladacycles have been tested: *i*) dinuclear complexes of the *CN* type derived from azoarenes (Chart 2, type **M**),[167, 168, 172] ii) mononuclear complexes based on azoarenes and having an additional cyclopentadienyl ligand (**N**),[151, 173] iii) mononuclear complexes based on azoarenes with an SR (**O**)[162, 163, 166, 171] or another chelating substituent (**P**),[164, 165] iv) dinuclear complexes of the *CS* type obtained from dibenzyl sulfide, benzyl phenyl sulfide and benzyl phenyl sulfoxide (**Q**),[174] and v) mononuclear complexes derived from 2-(dimethylamino)methylnaphthalene (**R**).[176] Here I present data for the reactions of *m*-CPBA with dimeric dichloro- and diacetato-bridged CPCs derived from 2-phenyl-2-oxazolines.

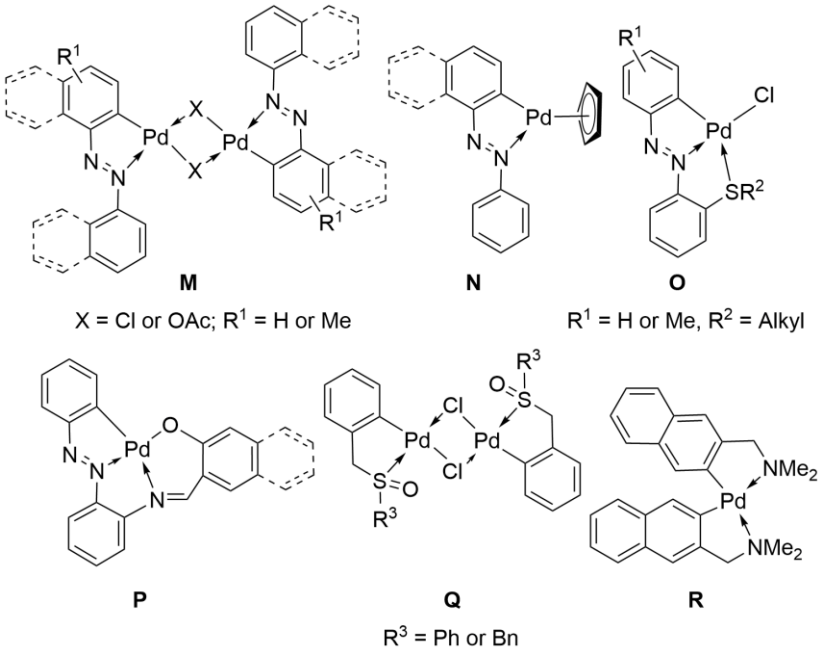
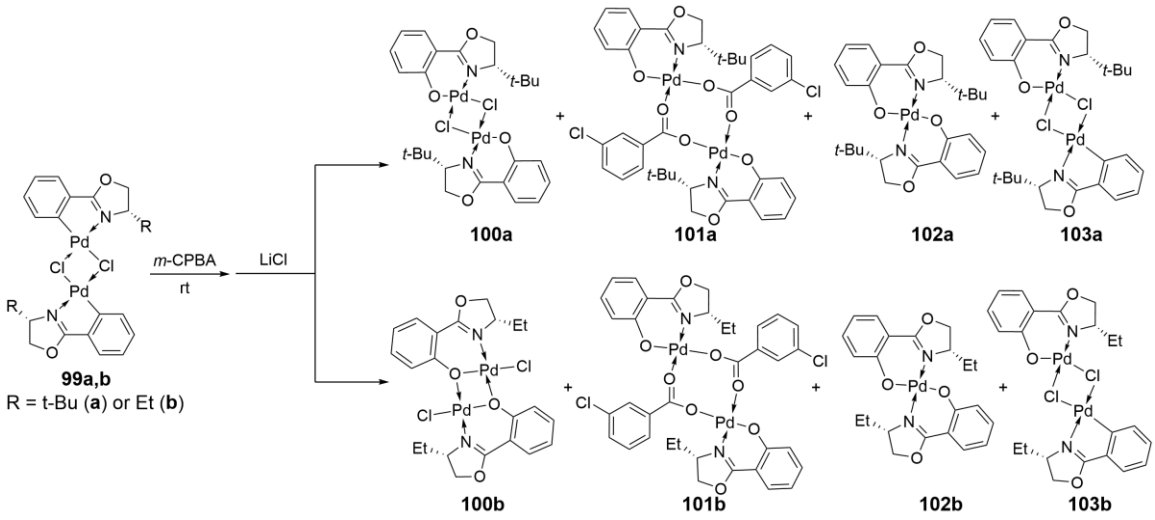


Chart 2. Cyclopalladated complexes **M**−**R** used in reported reactions with *m*-CPBA.

II.3.2. Reactions of CPCs with m-*Chloroperoxybenzoic Acid*

The chloro-bridged complex **99**[186] previously reported by our group was chosen as a model compound for this study. The dimeric complex reacted with 2.7 molar equivalents of *m*-CPBA in ethyl acetate (EtOAc) at room temperature (rt). The reaction mixtures were treated with excess LiCl to minimize the products containing bridging *m*-chlorobenzoate ligands by replacing them with chloride ions. After 18 h, the reaction mixture contained several products, four of which were isolated and characterized by NMR spectroscopy: dimeric dichloro-bridged complex **100a**, di-*m*-chlorobenzoato-bridged analog **101a**, the corresponding bis(κ^2*N*,*O*)Pd complex **102a** and the dimeric mono-insertion complex **103a** (Scheme 35 and Table 14).



Scheme 35. Reactions of complexes **99a,b** with *m*-CPBA.

Table 14. Yields of the products formed in the reaction of complex **99a** with 2.7 equivalents of *m*-CPBA at rt.

Entry	Solvent	Time, h	Yield*, %, of the Corresponding Product			
			100a	**101a**	**102a**	**103a**
1	CH_2Cl_2	0.5	7	†	20	†
2	EtOAc	18	(8)	(5)	13 (16)	13
3	MeCN	18	(13)	7 (12)	20	6 (12)

*Yields of isolated pure compounds are given. In some cases, yields were calculated using ^{1}H NMR spectra; such yields are given in parentheses.

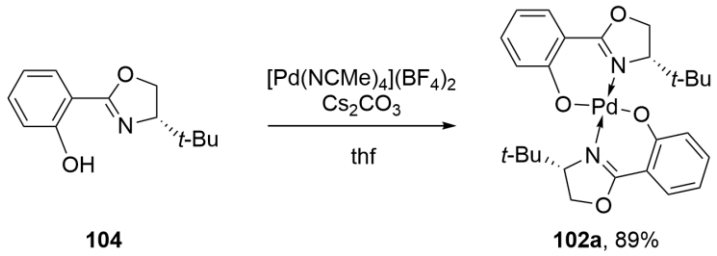
†No product was detected in the ^{1}H NMR spectrum of the reaction mixture.

Complexes of type **100** were previously described in reactions of dimeric dichloro-bridged CPCs with various oxidants including *m*-CPBA; they are one of the two types of oxygen-insertion products reported in these studies.[174, 176-178, 182] It appears that type-**100** complexes are relatively unstable, especially during chromatographic purification and gradually produce the corresponding compounds of type **102** as well as, presumably, $PdCl_2$. A tendency for decomposition was also noted for one of the azobenzene-derived complexes of this type, and likewise, it was proposed that the corresponding bis(κ^2-*N,O*)Pd complexes of type **102** were produced along with $PdCl_2$.[182]

Formation of the dimeric di-*m*-chlorobenzoato-bridged *N,O*-complexes of type **101** has never been reported in reactions of CPCs with *m*-CPBA. However, in the present work, complexes of this type were isolated practically in all reactions even after addition of excess LiCl. In particular, complex **101a** was obtained in chromatographically pure form with a maximum yield of 12% (Table 14). When silver *m*-chlorobenzoate was added to the reaction mixture (EtOAc, 18 h) after the oxidation step, the yield of **101a** was increased to 22%. ^{1}H and $^{13}C\{^{1}H\}$ NMR spectra of complex **101a** in $CDCl_3$ contained one set of signals, suggesting that it exists in solution in the form of a single geometrical isomer. The presence of two different organic ligands in a ratio of 1:1 in the structure of **101a** was evident from the NMR spectra. The most salient feature of the ^{1}H NMR spectrum of compound **101a** was the presence of resonance signals in the region of 6.5–6.9 ppm assigned to two aromatic hydrogens of the C_6H_4 fragment of the oxazoline ligand. Such a high-field shift for the signals of aromatic hydrogens in *N,O*-Pd(II) complexes compared to those of the starting CPCs was noted in other studies.[168, 171, 178]

Complex **102a** was isolated in 13% yield when standard reaction conditions were used (EtOAc, rt, 18 h). This yield remained about the same when the reaction was performed in other solvents (CH_2Cl_2 and MeCN) and at elevated temperature (40 °C). As in the case of complex **101a**, the ^{1}H NMR spectrum of compound **102a** had signals of two aromatic hydrogens below 7 ppm. To eliminate the possibility of a dimeric dichloro-bridged structure, complex **102a** was independently synthesized by reaction of (*S*)-2-(2'-hydroxyphenyl)-4-*t*-butyl-2-oxazoline (**104**) with $[Pd(NCMe)_4](BF_4)_2$ in the presence of Cs_2CO_3 (Scheme 36). The ^{1}H and ^{13}C NMR spectra of the oxidation product and the complex synthesized from oxazoline **104** were identical. Furthermore, complex **102a** was

found to crystallize readily into X-ray quality crystals, and X-ray diffraction analysis was performed (*vide infra*), unambiguously confirming the proposed structure. It should be mentioned that (oxazolinyl-κ^2*N,O*)$_2$Pd(II) complexes of type **102** have been reported[187-189] and some of them are active catalysts in allylic acetoxylation of alkenes.[187]



Scheme 36. Preparation of complex **102a** from oxazoline **104**.

Complexes of type **103**, in which only one out of two palladacycles in the starting dimer underwent oxygen insertion, were previously reported in oxidation reactions of *cis*-(κ^2-*C,N*)$_2$Pd complex **R** with *t*-BuOOH.[176] In the reaction of CPC **99a** with 2.7 equivalents *m*-CPBA, dinuclear monooxidation complex **103a** was one of the major products (Scheme 35 and Table 14). Attempts to minimize the formation of the monooxidation product by increasing the amount of *m*-CPBA up to 5 equivalents resulted in an insignificant decrease in the yield of **103a** and greater yields of **101a**. Raising the temperature to 40 °C did not affect either the yields or selectivity of the reaction.

The ^{1}H NMR spectrum of complex **103a** exhibited signals from two different 2-phenyl-2-oxazoline-derived ligands in a 1:1 ratio. For one of the two C_6H_4 fragments, all four protons provided well-resolved signals (COSY data); two of these signals appeared at 6.47 and 6.71 ppm suggesting oxygen insertion for this ligand. The other C_6H_4 group provided two multiplets with an integration of 3H and 1H and centered at 7.45 and 8.42 ppm, respectively. Such a pattern is typical for the C_6H_4 fragment of *C,N*-CPCs derived

from 2-phenyl-2-oxazoline ligands.[186, 190, 191] Therefore, it is suggested that only one aromatic group of the two oxazoline ligands in complex **103a** is connected to an oxygen atom. To eliminate the possibility of a mononuclear structure for compound **103a**, it was treated with $AgBF_4$. The immediate appearance of a precipitate suggests that complex **103a** contains chlorine atoms and is likely to have a dimeric structure as shown in Scheme 35.

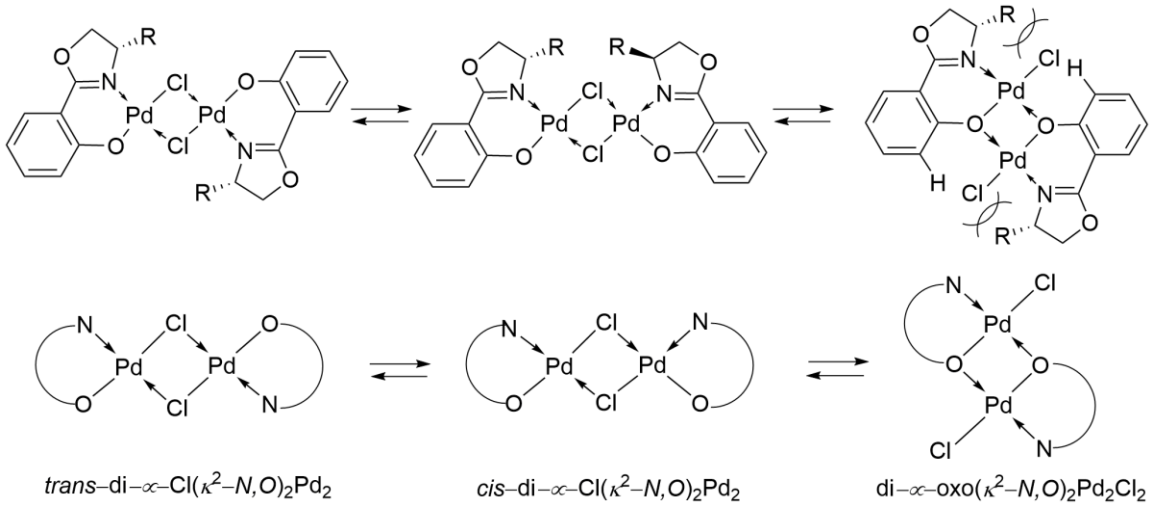
Metaloxylation using *m*-CPBA was further investigated in reactions with the dimeric dichloro-bridged CPC **99b** (Scheme 35). Different solvents (EtOAc, CH_2Cl_2 and MeCN) and reaction times (0.5 and 18 h) were tested. In all cases, complex mixtures of products were formed. Four oxidation products, **100b**−**103b**, were isolated and characterized by NMR spectroscopy (Table 15). When the reaction mixtures of **99b** in EtOAc were subsequently treated with excess LiCl, the result was a disappearance of **101b** (Table 15, entries 1 and 2). However, when MeCN was used as a solvent for the oxidation reaction, **101b** was isolated in 15% yield. When the reaction mixture (EtOAc, 0.5 h) was treated with silver *m*-chlorobenzoate, complex **101b** was obtained in a comparable yield (19%). When excess LiCl was added to the reaction mixture, compounds **100b, 102b**, and **103b** were isolated in 9, 11, and 11% yield, respectively.

Table 15. Yields of the products formed in the reaction of complex **99b** with 2.7 equivalents of *m*-CPBA at rt.

Entry	Solvent	Time, h	Yield*, %, of the Corresponding Product			
			100b	**101b**	**102b**	**103b**
1	EtOAc	0.5	9	†	11	11
2	EtOAc	18	(16)	†	4	30 (32)
3	MeCN	18	6 (12)	15 (18)	7 (8)	(13)

* Yields of isolated pure compounds are given. In some cases, yields were calculated using ^{1}H NMR spectra; such yields are given in parentheses.
† No product was detected in the ^{1}H NMR spectrum of the reaction mixture.

The ^{1}H and $^{13}C\{^{1}H\}$ NMR spectra of product **100b** in $CDCl_3$ contained one set of signals, just as the spectra of **100a** and related dimeric dichloro-bridged complexes of this type obtained from compounds **M** and **P** shown in Chart 2. The spectra of **100b** contained only signals of the 2-phenyl-2-oxazoline-derived moiety and were different from those of related compounds with the same ligand such as the starting CPC **99b**, the corresponding free oxazoline (HL), the coordination complex $(HL)_2PdCl_2$[191] and the previously reported mononuclear complex **102b**.[189] Moreover, signal patterns in the spectra of **100a** and **100b** were different. Most importantly, in contrast to the oxygen-insertion products **100a**, **101a,b** and **102a,b**, the ^{1}H NMR spectrum of **100b** did not have any signals of aromatic hydrogens below 7 ppm. It is likely that product **100b** has the di-μ-oxo(κ^2-*N*,*O*)$_2$Pd$_2$Cl$_2$ structure (see Scheme 37) in $CDCl_3$ solutions. Such oxygen-bridged structures for this type of complex were proposed by the research group of van Koten.[178] They reported that oxidation of the dimeric dichloro-bridged *N*,*N*-dimethylbenzylamine-derived CPC by *t*-BuOOH in the presence of a vanadium catalyst resulted in the formation of three isomeric products: *trans*-di-μ-Cl(κ^2-*N*,*O*)$_2$Pd$_2$, *cis*-di-μ-Cl(κ^2-*N*,*O*)$_2$Pd$_2$ and di-μ-oxo(κ^2-*N*,*O*)$_2$Pd$_2$Cl$_2$ in a ratio of 1:1:9.4 (Scheme 37).[178] The authors noted that the di-μ-oxo(κ^2-*N*,*O*)$_2$Pd$_2$Cl$_2$ isomer provided a characteristic low-field ^{1}H NMR signal assigned to the aromatic hydrogen ortho to the C−O bond. In the ^{1}H NMR spectrum of complex **100b**, there was a doublet of the ortho hydrogen at 8.32 ppm. According to van Koten, such a low-field shift is due to a close proximity of the corresponding hydrogen to the chlorine atom.[178] For comparison, in the ^{1}H NMR spectrum of the coordination complex $(HL)_2PdCl_2$ (HL is (*S*)-4-ethyl-2-phenyl-2-oxazoline) the ortho hydrogen provides a doublet at 8.87 ppm because of the hydrogen's proximity to chlorine.[191]



Scheme 37. Possible isomeric forms of complexes **100a,b** in solution.

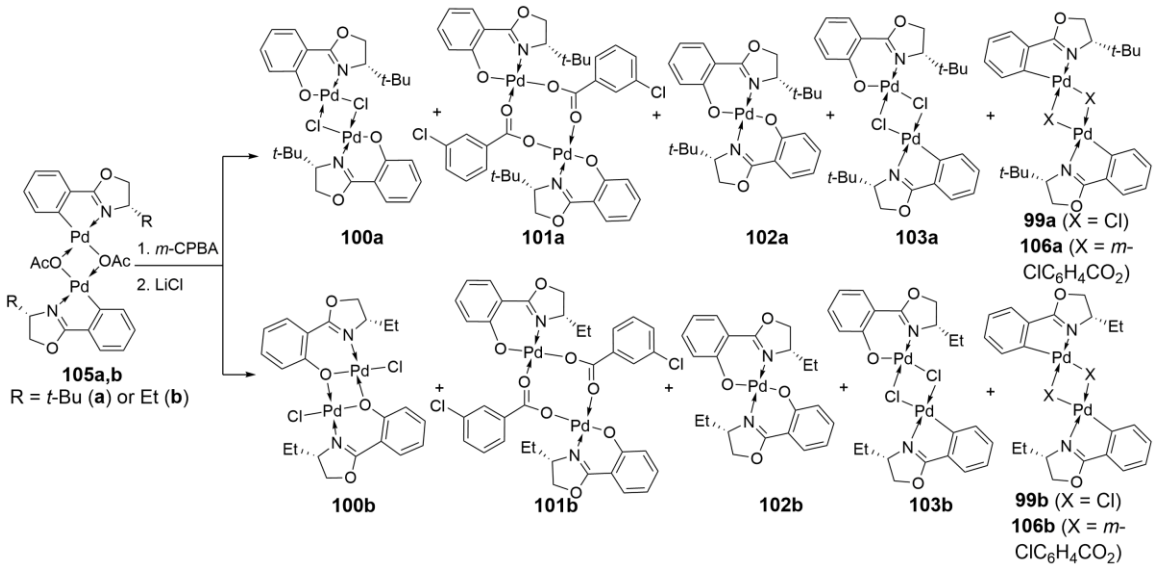
In contrast, the *t*-butyl analog of complex **100b** appears to have a *trans*-dichloro-bridged structure in $CDCl_3$ solutions. The most plausible reason is that the bulky *t*-butyl groups in **100a** have a greater interaction with the chloride ligand, making the di-μ-oxo(κ^2-*N*,*O*)$_2$Pd$_2$Cl$_2$ geometry less likely (Scheme 37).

The ^{1}H and ^{13}C{^{1}H} NMR spectra of complex **101b** had the same general features as those of **101a**: *i*) one set of signals, *ii*) a 1:1 ratio of the oxazoline-derived ligand and *m*-$ClC_6H_4CO_2$ fragment, and *iii*) two characteristic signals of the aromatic moiety were apparent, in this case, at 6.52 and 6.82 ppm. The elemental composition of both complexes **101a,b** was confirmed by satisfactory elemental analysis.

Preparation and ^{1}H NMR data of complex **102b** have been reported; it was synthesized from the corresponding phenol,[189] and the NMR data are consistent with those obtained for compound **102b** isolated in our study.

The ^{1}H and ^{13}C NMR spectra of complex **103b** were very similar to those of the analogous *tert*-butyl substituted oxazoline complex **103a** and contained the same characteristic signals, as described above.

There is only one report of *m*-CPBA oxidation of μ-OAc CPCs. Bhawmick et al. reported that the dimeric diacetato-bridged complex **M** derived from 1-(1'-naphthylazo)naphthalene (see Chart 2) reacted with *m*-CPBA to give the oxygen-insertion product having a dimeric diacetato-bridged structure in 30% yield.[172] In our study, two previously reported μ-OAc CPCs **105a,b** were tested in reactions with *m*-CPBA (Scheme 38). The ^{1}H NMR spectra of the reaction mixtures taken after 30 min (EtOAc, rt, no LiCl treatment) showed no signals of the starting CPCs. In spite of the fact that these spectra had signals between 6 and 7 ppm, which are characteristic of oxygen insertion products, only *m*-chlorobenzoato-bridged CPCs **106a,b** were isolated in pure form in 29 and 22% yield, respectively. When the reaction mixture of complex **105a** with *m*-CPBA (EtOAc, 18 h, rt) was treated with excess LiCl, two oxidation products **100a** and **102a** were isolated in 15 and 3% yield, respectively (Table 16). A significant amount of the non-oxidized CPC **99a** was recovered as well. (The dimeric acetato- and *m*-chlorobenzoato-bridged complexes **105a,b** and **106a,b** readily undergo conversion to the corresponding dichloro-bridged analogs upon treatment with LiCl.) Reaction of **105b** under the same conditions provided three oxidation products, **100b**, **102b** and **104b**, in very low yield (Table 17). The non-oxidized CPC **99b** was isolated in 22% yield.



Scheme 38. Reactions of complexes **105a,b** with *m*-CPBA.

Table 16. Yields of the products formed in the reaction of complex **105a** with 2.7 equivalents of *m*-CPBA (18 h, rt).

Entry	Solvent	Yield*, %, of the Corresponding Product					
		100a	**101a**	**102a**	**103a**	**99a**	**106a**
1	EtOAc	15	†	3	†	37	†
2	MeCN	46	(13)	5	†	7	6

* Yields of isolated pure compounds are given. In some cases, yields were calculated using ^{1}H NMR spectra; such yields are given in parentheses.

† No product was detected in the ^{1}H NMR spectrum of the reaction mixture.

Table 17. Yields of the products formed in the reaction of complex **105b** with 2.7 equivalents of *m*-CPBA (18 h, rt).

Entry	Solvent	Yield*, %, of the Corresponding Product					
		100b	**101b**	**102b**	**103b**	**99b**	**106b**
1	EtOAc	2	†	2	(8)	22	6
2	MeCN	†	(7)	44	†	15 (17)	1

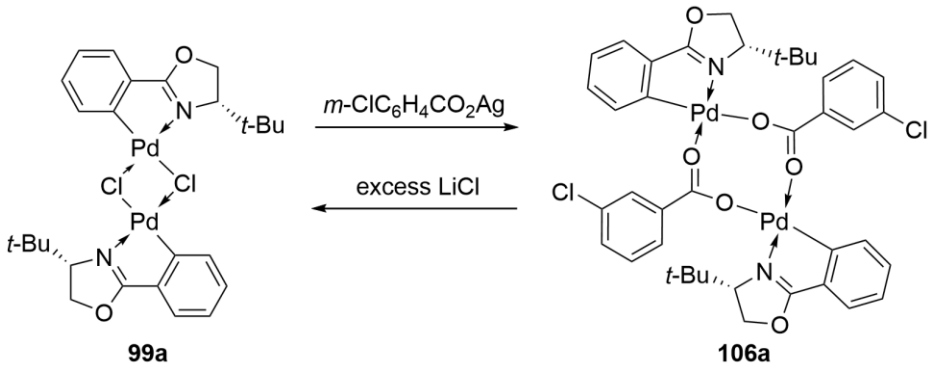
* Yields of isolated pure compounds are given. In some cases, yields were calculated using ^{1}H NMR spectra; such yields are given in parentheses.

† No product was detected in the ^{1}H NMR spectrum of the reaction mixture.

When reactions of **105a,b** with *m*-CPBA were carried out in MeCN (18 h, rt, LiCl treatment), the total yields of oxidation products were higher, but unreacted palladacycles **99a** and **99b** were isolated once again (Tables 16 and 17).

Complexes **106a,b** were assigned the dimeric di-*m*-chlorobenzoato-bridged structure based on NMR and IR data. Their elemental composition was confirmed by satisfactory elemental analysis. The IR spectrum of **106a** displayed two strong bands at 1562 and 1389 cm^{-1}, corresponding to vibrations of the COO moiety.[192] For comparison, the IR spectrum of the metaloxylation product **102a,** also having a dimeric *m*-chlorobenzoato-bridged structure, exhibited two bands of the COO fragment at 1560 and 1395 cm^{-1}. ^{1}H NMR spectra of complexes **106a,b** did not have signals between 6 and 7 ppm, while other complexes with the C−O−Pd fragment, except for the oxo-bridged isomer **100b**, had two such signals. All di-*m*-chlorobenzoato-bridged complexes of type **102** and **106** had one set of signals in ^{1}H and $^{13}C\{^{1}H\}$ NMR spectra suggesting that these dimers are single geometric isomers in solutions.

To rule out the possibility that compounds **106a,b** contained peroxybenzoate ligands, the dichloro-bridged complex **99a** was reacted with silver *m*-chlorobenzoate to give the corresponding di-*m*-chlorobenzoato-bridged complex (Scheme 39). The ^{1}H NMR spectra of the obtained product and complex **106a** were identical. This observation also served as confirmation that complex **106a** does not contain a C–O–Pd moiety. Further verification was obtained by reacting **106a** with excess LiCl. This transformation yielded complex **99a** in >95% yield (Scheme 39).



Scheme 39. Ligand exchange reactions of complexes **99a** and **106a**.

In our study, metaloxylation of dimeric 2-phenyl-2-oxazoline-derived CPCs with *m*-CPBA resulted in low yields of the oxygen insertion products. For comparison, the only study to date of *m*-CPBA oxidation involving a dimeric acetato-bridged CPC [derived from 1-(1-naphthylazo)naphthalene] reported a 30% yield of the corresponding μ-OAc *N,O*-complex.[172] In other metaloxylation reactions with *m*-CPBA, the yields of the oxygen insertion products were ranging from 45[172] to 60%[167] for the μ-Cl-*C,N* complexes derived from azoarenes (compounds of type **M**, see Chart 2) and from 30 to 60% for the μ-Cl-*C,S* analogs (type **P**). Mononuclear *C,N*, *C,N,S* and *C,N,N* azoarene derivatives (complexes of types **N**−**O**) provided even higher yields, up to 90%.[168, 176] It appears that all reported reactions of azoarene-derived CPCs, which are likely to have poor solubility in the majority of organic solvents, were performed in MeCN.

Oxazoline-derived CPCs **99a,b** and **105a,b** are soluble in the majority of organic solvents. In our metaloxylation experiments, several solvents were tested (CH_2Cl_2, EtOAc, thf, PhMe and MeCN) for the oxidation. The best results were obtained in the coordinating solvent MeCN, while reactions in other solvents, particularly EtOAc and CH_2Cl_2, provided lower yields. The solvent effect was especially noticeable for acetato-bridged complexes

105a,b. Thus, in the reactions of complex **105a** performed in EtOAc and then in MeCN, the total yield of oxidation products **100a**−**103a** rose from 18% to 64%. The total yield of **100b**−**103b** in oxidation reactions of **105b** increased from 12% in EtOAc to 51% in MeCN.

Comparison of the results obtained for metaloxylation of μ-Cl-CPCs **99a,b** with those for μ-OAc-CPCs **105a,b** shows that the former complexes are more reactive in both EtOAc and MeCN. Thus, in the reactions of **105a,b** significant amounts (7−37%) of the non-oxidized complexes (μ-Cl-derived **99a,b** and *m*-$ClC_6H_3CO_2$-bridged **106a,b**) were isolated, while no starting CPCs were recovered in the reactions of μ-Cl-CPCs **99a,b**. The use of *m*-CPBA in high excess for reactions with CPCs **105a,b** did not prevent the formation of *m*-$ClC_6H_3CO_2$-bridged **106a,b**, which apparently have low reactivity towards *m*-CPBA just like their *m*-OAc analogs. Therefore, when selecting complexes and conditions for metaloxylation reactions with *m*-CPBA, it may be best to employ ligands possessing a stronger trans influence.

According to the mechanism proposed for oxygen-insertion reactions of CPCs with peroxy acids,[185] oxidation by electrophilic *m*-CPBA is accelerated with increased nucleophilicity of the carbon bonded to the metal. By replacing EtOAc with the coordinating solvent MeCN, dimeric complexes are converted to mononuclear derivatives with MeCN acting as an auxiliary ligand. In these complexes, chloride and acetate ligands are monodentate. As such, they should have a stronger bond to the metal and therefore a greater trans influence on the Pd–C bond compared to bridging Cl and AcO ligands. To illustrate, the Pd–C bond length in the dimeric chloro-bridged CPC of (*R*)-1-phenylethylamine is 1.946 Å, while the same bond trans to the monodentate Cl ligand in the corresponding mononuclear complex PPh_3 adduct is longer, 1.971 Å (the average for

two independent molecules).[193] Because the reactions of CPCs **99a,b** and **105a,b** in MeCN provided higher yields of oxidation products, it appears that the monodentate Cl and OAc ligands not only lengthened the Pd–C bond but also increased the nucleophilicity of the carbon bonded to the metal.

The importance of the increased nucleophilicity of the palladium-bound carbon in achieving higher yields of metaloxylation can be demonstrated by comparing the NMR data and yields in reported reactions of CPCs with *m*-CPBA. One of the parameters determining nucleophilicity of a given atom is the electron density around the nucleus, which can be estimated using its chemical shift in NMR data. For dimeric μ-Cl and μ-OAc CPCs **99a,b** and **105a,b**, the ^{13}C NMR chemical shift of the carbon bonded to the palladium was observed between 145 and 148 ppm (in $CDCl_3$). The carbon bonded to the metal in the mononuclear CPC **N** (Chart 2) gives a ^{13}C NMR signal at 189 ppm,[173] while the corresponding carbon of the dimeric μ-OAc derivative of 1-(phenylazo)naphthalene (a complex of type **M**) resonated at 161 ppm].[194] On the basis of these data, CPCs derived from azoarenes (complexes of type **M**), especially the one with the cyclopentadienyl moiety (complex **N**), are expected to be more prone to oxidation by *m*-CPBA compared to 2-phenyl-2-oxazoline-derived CPCs and are likely to give higher yields of oxidation products. Indeed, metaloxylation of complex **N** afforded the oxidation product in 65% yield (by NMR), while the dimeric μ-Cl derivative of 1-(1-naphthylazo)naphthalene (a type **M** complex) provided the corresponding μ-Cl *N,O*-analog in 45% yield.[172] Therefore, a possible reason for low yields of oxidation products for the dimeric 2-phenyl-2-oxazoline-derived CPCs is lower nucleophilicity of the carbon bonded to the palladium compared to the carbon in azoarene-based CPCs previously investigated in oxidation reactions.

II.3.3. Conclusions

Dimeric chloro- and acetato-bridged cyclopalladated complexes of 2-phenyl-2-oxazolines **99a,b** and **105a,b** react with *m*-CPBA at rt to give complex mixtures of oxygen insertion products, including di-μ-Cl(κ^2-*N*,*O*)$_2$Pd$_2$ (**100a,b**), di-μ-(*m*-ClC$_6$H$_3$CO$_2$)(κ^2-*N*,*O*)Pd$_2$ (**101a,b**), (κ^2-*N*,*O*)$_2$Pd (**102a,b**), and di-μ-Cl(κ^2-*N*,*O*)(κ^2-*C*,*N*)Pd$_2$ (**103a,b**) complexes. Yields of oxygen-insertion products were increased when the coordinating solvent MeCN was used.

CHAPTER III

EXPERIMENTAL SECTION

III.1. General Procedures and Instrumentation

All reactions of $HPPh_2$ were carried out under an argon atmosphere using Schlenk techniques. Purifications by column chromatography were carried out using Natland silica gel 60 (230 mesh). Preparative thin-layer chromatography (TLC) was carried out using 200 × 250 mm glass plates with an unfixed layer of Natland or Merck silica gel 60 (230 mesh). Analytical TLC was performed on Whatman silica gel 60 (F_{254}) 250 μm precoated plates. Compounds were visualized on TLC plates using UV light (254 nm) and/or iodine stains. Routine ^{1}H (500 MHz), $^{13}C\{^{1}H\}$ (126 MHz) and $^{31}P\{^{1}H\}$ (202 MHz) NMR spectra as well as DEPT, COSY and HSQC spectra were recorded on a Bruker AVANCE 500 NMR spectrometer. Chemical shifts are reported in ppm with $SiMe_4$ as an internal standard (^{1}H and ^{13}C) or $P(OEt)_3$ as an external standard (^{31}P). Spin-spin coupling constants, *J*, are given in Hz. Spectra of the products obtained were recorded in $CDCl_3$ unless otherwise stated. Melting points were measured on a Laboratory Devices Mel-Temp apparatus and are uncorrected. Optical rotations were measured at room temperature on a Rudolph Autopol III automatic polarimeter or a JASCO P-2000 series digital polarimeter using a 1-dm tube. Elemental analyses were carried out by *Atlantic Microlabs Inc.*, Norcross, GA. Mass spectrometry analyses were conducted on an Agilent 1100 HPLC coupled to a high resolution Time of Flight MS G1689A Series 6200. Samples were injected directly to the

mass spectrometer. Electrospray ionization was performed in a positive mode. Drying gas (N_2) was set to 350 °C at a flow rate of 12 L/min and the nebulizer gas (N_2) pressure was set to 25 psi. The MS data were acquired in the full scan mass range of 100–1000 m/z.

The starting cyclopalladated complexes were synthesized by known procedures from *N*,*N*-dimethylbenzylamine (**L41**), 2-*tert*-butyl-4,4-dimethyl-2-oxazoline (**L77**), 8-methylquinoline (**L81**), tri-*o*-tolylphosphine (**L83**), the *O*-methyloximes of L-fenchone (**L85**)[58] and D-camphor (**L86**), (*S*)-4-*tert*-butyl- (**L98a** and **104a**)[186] and (*S*)-4-ethyl-2-phenyl-2-oxazoline (**L98b** and **104b**).[191] **L96** was synthesized[195] from L-*tert*-leucinol ordered from *Sigma Aldrich Co*. Benzene, toluene, tetrahydrofuran, and their deuterated analogs were dried by refluxing over K/benzophenone ketyl, distilled under Ar, and stored over potassium. Acetone was purified by distillation over $KMnO_4$. Other solvents were dried over CaH_2. All commercially available reagents were used as received from the supplier, unless otherwise noted. Secondary phosphines were obtained from *Sigma Aldrich Co.* *m*-Chloroperoxybenzoic acid (*m*-CPBA, 0.2 g) was dissolved in 14 mL of ether and washed with pH 7.5–8.0 phosphate (KH_2PO_4 and NaOH) buffer (3 × 9 mL). The solution was dried over Na_2SO_4, and then the solvent was removed on a rotavapor. The purity of the purified *m*-CPBA was >95% (NMR data).

III.2. Preparation of Products from the Reaction of CPCs with Secondary Phosphines

III.2.1. General Procedure for Phosphination Reactions

The CPC was placed into an Ar-filled 10-mL Schlenk flask with nine equivalents of Cs_2CO_3, a rubber septum was inserted, and the solvent was introduced by syringe (1 mL per 5 mg of complex, unless noted otherwise). The flask was lowered into an oil bath heated to the reaction temperature. Once the CPC was completely dissolved, the secondary

phosphine was added dropwise for 2 minutes either as a neat liquid or as a 1M toluene solution. The reaction mixture was stirred in an Ar atmosphere for 18 h unless otherwise stated. The solvent was removed at reduced pressure and the crude mixture was separated by preparative thin layer chromatography on silica gel. Additional experimental details are described below.

III.2.2. Compounds Synthesized from Reactions of CPCs with Secondary Phosphines

2-Methyl-2-(4,4-dimethyloxazolin-2-yl)propyldiphenylphosphine (78). CPC **77** (0.0261 g, 0.0442 mmol) was reacted with 9 equivalents of $HPPh_2$ in CH_2Cl_2 at 35 °C according to the general procedure. After solvent removal, the solid residue was purified using preparative TLC (7:1 benzene–acetone). Iminophosphine **78** was obtained in as a pale yellow syrup in the amount of 12.2 mg (56%). R_f 0.61 (6:1 hexane–ethyl acetate). ^{1}H NMR (δ, ppm): 1.17 (s, 6H, $C(CH_3)_2$), 1.30 (s, 6H, $NC(CH_3)_2$), 2.43 (d, 2H, $^2J_{HP}$ = 3.6, PCH_2), 3.66 (s, 2H, OCH_2), 7.29 (br. m, 5H, *m*- and *p*-PPh), 7.44 (dt, $^3J_{HH}$ = 7.5, $^3J_{HP}$ = 1.4, 4H, *o*-PPh). $^{13}C\{^1H\}$ NMR (δ, ppm): 27.5 (d, $^3J_{CP}$ = 9.7, $C(\underline{C}H_3)_2$), 28.2 ($NC(\underline{C}H_3)_2$), 36.5 (d, $^2J_{CP}$ = 17.2, $PCH_2\underline{C}(CH_3)_3$), 41.1 (d, $^1J_{CP}$ = 16.8, PCH_2), 66.8 ($N\underline{C}(CH_3)_2$), 78.7 (OCH_2), 128.3 (d, $^3J_{CP}$ = 6.5, *m*-PPh), 129.1 (*p*-PPh)), 132.9 (d, $^2J_{CP}$ = 19.5, *o*-PPh), 139.6 (d, $^1J_{CP}$ = 12.6, *ipso*-PPh), 170.9 (d, $^3J_{CP}$ = 2.2, OC=N). $^{31}P\{^1H\}$ NMR (δ, ppm): -37.8. HRMS: $[M + H]^+$ calcd for $C_{21}H_{27}NOP^+$ 340.18303, found 340.18302.

***μ*-Chloro-*μ*-diphenylphosphido-[2-methyl-2-(4,4-dimethyloxazolin-2-yl)propyl-*C,N*]dipalladium(II) (79)**. Method I. CPC **77** (0.0235 mg, 0.0398 mmol) was reacted with 4.5 equivalents of $HPPh_2$ in toluene at 40 °C according to the general procedure. After solvent removal, the solid residue was dissolved in a minimal volume of $CHCl_3$ and

purified using preparative TLC (7:1 benzene–acetone). Complex **79** was isolated as a yellow solid in the amount of 7.1 mg (24%). Method II. CPC **77** (0.0271 mg, 0.0460 mmol) was reacted with 4.5 equivalents of $HPPh_2$ in toluene at 40 °C according to the general procedure in the presence of pyridine (7.5 μL, 0.092 mmol) instead of Cs_2CO_3. After solvent removal, the solid residue was purified using preparative TLC (7:1 benzene–acetone). Complex **79** was isolated as a yellow solid in in the amount of 13.7 mg (40%). ^{1}H and ^{31}P NMR data were identical to those previously reported for this compound.[57]

***cis*-(*C,P*^{1})-Diphenylphosphido-[2-methyl-2-(4,4-dimethyloxazolin-2-yl)propyl-*C,N*][2-methyl-2-(4,4-dimethyloxazolin-2-yl)propyldiphenylphosphine-*P*^{2}]palladium(II) (80)**. CPC **77** (0.0206 g, 0.0349 mmol) was reacted with 4.5 equivalents of $HPPh_2$ in toluene at 40 °C according to the general procedure. After solvent removal, the solid residue was purified using preparative TLC (7:1 benzene–acetone). Complex **80** was isolated as a pale yellow solid in 14.2 mg (52%). R_f = 0.72 (7:1 benzene–acetone); m.p. 154–156 (dec). ^{1}H NMR (δ, ppm, C_6D_6): 0.50 (s, 6H, $C(CH_3)_2$), 1.15 (s, 2H, $PdC\underline{H}_2C(CH_3)_2$), 1.20 (s, 6H, $C(CH_3)_2$), 1.19 (s, 6H, $NC(CH_3)_2$), 1.22 (s, 6H, $NC(CH_3)_2$), 1.43 (d, 2H, $^{2}J_{HP}$ = 2.1, PCH_2), 3.31 (s, 2H, OCH_2), 3.41 (s, 2H, OCH_2), 7.01 (2, 2H, $^{3}J_{HH}$ = 7.5, *p*-PPh), 7.05 (br. m, 2H, *p*-PPh), 7.16 (br. m, 4H, *o*-PPh), 7.23 (dt, 4H, $^{3}J_{HH}$ = 7.5, $^{3}J_{HP}$ = 1.6, 4H, *o*-PPh), 8.12 (dt, $^{3}J_{HH}$ = 8.6, $^{2}J_{HP}$ = 1.2, 4H, *m*-PPh), 8.19 (dt, $^{3}J_{HH}$ = 8.9, $^{4}J_{HP}$ = 1.3, 4H, *m*-PPh). $^{13}C\{^{1}H\}$ NMR (δ, ppm, C_6D_6): 25.57 ($C(\underline{C}H_3)_2$), 26.08 ($NC(\underline{C}H_3)_2$), 27.05 ($NC(\underline{C}H_3)_2$), 28.4 (d, $^{3}J_{CP}$ = 9.7, $C(\underline{C}H_3)_2$), 29.8 (CH_2PdPPd), 40.4 ($PdCH_2\underline{C}(CH_3)_3$), 40.4 (d, $^{2}J_{CP}$ = 2.9, $PCH_2\underline{C}(CH_3)_3$), 41.8 (d, $^{1}J_{CP}$ = 77.3, PCH_2), 64.3 ($N\underline{C}(CH_3)_2$), 65.1 (d, $^{3}J_{CP}$ = 3.2, $N\underline{C}(CH_3)_2$), 79.8 (OCH_2), 80.2 (OCH_2), 126.0 (*p*-PPh), 126.1 (d, $^{3}J_{CP}$ = 2.6, *m*-PPh), 127.1 (d, $^{3}J_{CP}$ = 2.6, *m*-PPh), 127.5 (d, $^{4}J_{CP}$ = 1.5, *p*-PPh),

131.1 (d, $^2J_{CP}$ = 11.3, *o*-PPh), 133.6 (d, $^2J_{CP}$ = 12.7, *o*-PPh), 142.2 (d, $^1J_{CP}$ = 7.9, *ipso*-PPh), 143.4 (d, $^1J_{CP}$ =55.3, *ipso*-PPh), 180.4 (OC=N), 183.7 (d, $^3J_{CP}$ = 6.6, OC=N). $^{31}P\{^1H\}$ NMR (δ, ppm, C_6D_6): 7.8 (d, $^2J_{PP}$ = 38, $PdPPh_2CH_2$), 116.8 (d, $^2J_{PP}$ = 38, $PdPPh_2$). $^{31}P\{^1H\}$ NMR (δ, ppm, $CDCl_3$): –5.4 (d, $^2J_{PP}$ = 38, $PdPPh_2CH_2$), 102.5 (d, $^2J_{PP}$ = 38, $PdPPh_2$). Anal. calcd for $C_{42}H_{52}Cl_2N_2O_2P_2Pd_2$: C, 52.41; H, 5.45; N, 2.91%. Found: C, 52.02; H, 5.54; N, 2.86%.

8-[(Diphenyloxophosphino)methyl]quinoline (82). CPC **81** (0.0179 g, 0.0316 mmol) was reacted with 9 equivalents of $HPPh_2$ in CH_2Cl_2 at 35 °C according to the general procedure. The mixture was brought to rt, ethyl acetate was added in a 3:2 ratio with CH_2Cl_2, and 70 μL of 30% aqueous solution of H_2O_2 was added dropwise. The mixture was allowed to stir for an additional 2 h at rt. After solvent removal, the solid residue was purified using preparative TLC (4:1 CH_2Cl_2–acetone; the fraction with compound **82** was washed with copious amounts of 4:1 hexane–acetone). The aminophosphine oxide was isolated as a pale yellow oil in the amount of 13.1 mg (60%). ^1H and $^{31}P\{^1H\}$ NMR data were identical to those previously reported for this compound.[57]

[2-(Di-*ortho*-tolylphosphino)benzyl]diphenylphosphine oxide (84). Complex **83** (0.0193 g, 0.0217 mmol) was reacted with 9 equivalents of $HPPh_2$ in CH_2Cl_2 at 35 °C according to the general procedure. Air was then bubbled through the crude mixture for approximately 5 h. After solvent removal, the solid residue was purified using preparative TLC (4:1 hexane–acetone). The product was obtained as pale yellow oil in the amount of 12.5 mg (51%). ^1H and $^{31}P\{^1H\}$ NMR data were identical to those previously reported for this compound.[57]

(1*S*,4*S*)-1-{(Diphenylphosphino)methyl}-3,3-dimethylbicyclo[2.2.1]heptan-2-one *O*-Methyloxime (49). CPC **85** (14.8 g, 0.0230 mmol) was reacted with 9 equivalents of

$HPPh_2$ in CH_2Cl_2 at 35 °C according to the general procedure. After solvent removal, the solid residue was purified using preparative TLC (1:1 CH_2Cl_2–hexane). The UV-visible band near the bottom of the plate contained the product as a pale yellow oil in the amount of 10.2 mg (61%). ^1H and $^{31}P\{^1H\}$ NMR data were identical to those previously reported for this compound.[57]

(1*S*,4*R*)-1-{(Diphenylphosphino)methyl}-7,7-dimethylbicyclo[2.2.1]heptan-2-one *O*-Methyloxime (87) and (1*S*,4*R*)-1-{(Diphenyloxophosphino)methyl}-7,7-dimethylbicyclo[2.2.1]heptan-2-one *O*-Methyloxime (88). CPC **86** (0.0165 g, 0.0256 mmol) was reacted with 9 equivalents of $HPPh_2$ in toluene at rt according to the general procedure. After solvent removal, the solid residue was purified using preparative TLC (1:15 acetone–hexane). The UV-visible band near the middle of the plate contained **88** as a pale yellow oil in the amount of 4.0 mg (21%). The starting line was also collected. It was dissolved in ether and about twice the volume of hexane was added. The solution was filtered, the solvent was evaporated, and the orange-red residue was purified by preparative TLC (5:3 hexane–acetone) to obtain compound **88** as a pale yellow oil in the amount of 1.8 mg (9%). ^1H and ^{31}P NMR spectra of **87** and **88** were identical to those previously reported for these compounds.[57]

(1*S*,4*R*)-*cis*-(*P*,*P*)-Chloro(diphenylphosphido){1-[(diphenylphosphino)methyl]-7,7-dimethylbicyclo[2.2.1]heptan-2-one oxime}palladium (89). CPC **86** (0.0210 g, 0.0326 mmol) was reacted with 4.5 equivalents of $HPPh_2$ in toluene at 40 °C according to the general procedure. After solvent removal, the solid residue was purified using preparative TLC (3:2 hexanes–acetone). The product was obtained as a colorless solid in the amount of 7.2 mg (16%). R_f = 0.57 (24:1 CH_2Cl_2–CH_3OH); m.p. 180−182 (dec); $[\alpha]_D$ = –133º (*c*

0.165, acetone). ^{1}H NMR (δ, ppm): 0.66 (ddd, $^{2}J_{HH(6exo)}$ = 13.7, $^{3}J_{HH(5endo)}$ = 9.4, $^{3}J_{HH(5exo)}$ = 4.3, 1H, H(6endo)), 0.82 (s, 3H, CH_3), 0.83 (s, 3H, CH_3), 0.85 (m, 1H, H(6exo)), 1.05 (ddd, $^{2}J_{HH(5exo)}$ = 13.7, $^{3}J_{HH(6endo)}$ = 9.4, $^{3}J_{HH(6exo)}$ = 4.2, 1H, H(5endo)), 1.63 (dddd, $^{2}J_{HH(5endo)}$ = 12.1, $^{3}J_{HH(6exo)}$ = 8.9, $^{3}J_{HH(6endo)}$ = 4.3, $^{3}J_{HH(4)}$ = 0.9, 1H, H(5exo)), 1.88 (dd, $^{3}J_{HH(5exo)}$ = 7.6, $^{3}J_{HH(3exo)}$ = 3.5, 1H, H4), 1.94 (d, $^{2}J_{HH(3exo)}$ = 18.4, 1H, H(3endo)), 2.04 (dd, $^{2}J_{HP}$ = 16.2, $^{2}J_{HH}$ = 14.6, 1H, PCH_A), 2.13 (dd, $^{2}J_{HH}$ = 14.6, $^{2}J_{HP}$ = 6.9, 1H, PCH_B), 2.54 (br d, $^{2}J_{HH(3endo)}$ = 18.4, 1H, H(3exo), 7.11 (m, 4H, *o*-PPh), 7.21 (dt, $^{2}J_{HH}$ = 7.2, $^{3}J_{HH}$ = 1.3, 1H, *p*-PPh), 7.29 (m, 4H, *o*- and *p*-PPh), 7.52 (m, 7H, *o*-, *m*-, and *p*-PPh), 7.76 (m, 2H, *m*-PPh), 8.18 (m, 2H, *m*-PPh), 9.03 (s, 1H, NOH). ^{13}C{^{1}H} NMR (δ, ppm): 19.2 (CH_3), 20.0 (CH_3), 27.4 ($C(5)H_2$), 28.6 (d, $^{1}J_{CP}$ = 24.6, PCH_2), 29.4 ($C(6)H_2$), 41.8 (d, $^{4}J_{CP}$ = 4.8, $C(3)H_2$), 42.8 (C(4)H), 51.3 (d, $^{3}J_{CP}$ = 9.1, quat. C(7)), 57.9 (d, $^{2}J_{CP}$ = 1.9, quat. C(1)), 127.0 (*ipso*-PPh), 127.4 (d, $^{2}J_{CP}$ = 11.4, *o*-PPh), 127.7 (d, $^{2}J_{CP}$ = 11.4, *o*-PPh), 128.0 (d, $^{2}J_{CP}$ = 11.4, *o*-PPh), 129.0 (d, $^{3}J_{CP}$ = 11.4, *o*-PPh), 129.3 (d, $^{4}J_{CP}$ = 2.6, *p*-PPh), 129.4 (d, $^{4}J_{CP}$ = 2.6, *p*-PPh), 130.1 (d, $^{4}J_{CP}$ = 2.6, *p*-PPh), 131.4 (d, $^{3}J_{CP}$ = 10.7, *m*-PPh), 131.6 (d, $^{3}J_{CP}$ = 10.7, *m*-PPh), 131.7 (*ipso*-PPh), 132.4 (d, $^{4}J_{CP}$ = 2.1, *p*-PPh), 133.1 (d, $^{3}J_{CP}$ = 10.7, *m*-PPh), 136.7 (d, $^{3}J_{CP}$ = 13.3, *m*-PPh), 142.9 (*ipso*-PPh), 143.5 (*ipso*-PPh), 191.7 (C=N). ^{31}P{^{1}H} NMR (δ, ppm): 17.6 (d, J_{PP} = 12.2, $PdPPh_2CH_2$), 45.9 (d, J_{PP} = 12.2, $PdPPh_2$). HRMS: $[M - Cl^-]^+$ calcd for $C_{34}H_{36}NOP_2Pd^+$ 642.1301, found 642.1280.

1-{2-[Bis(4-methoxyphenyl)phosphino]phenyl}-*N*,*N*-dimethylmethanamine (42b). CPC **41** (18.1 mg, 0.0328 mmol) was reacted in CH_2Cl_2 with bis(4-methoxyphenyl)phosphine (73.0 mg, 0.296 mmol) according to the general procedure for 18 h at 35 °C followed by purification using preparative TLC (2:3 acetone–hexane). Aminophosphine **42b** was obtained in the amount of 15.7 mg (61% yield) as a colorless

oil. R_f = 0.57 (10:1 EtOAc–acetone). ^{1}H NMR (δ, ppm): 2.11 (s, 6H, N(CH_3)$_2$), 3.56 (d, 2H, $^4J_{HP}$ = 2, NCH_2), 3.8 (s, 6H, *p*-OCH_3) 6.86 (m, 5H, *m*-PAr and C(3)H arom), 7.14 (t, 1H, ^3J = 7, C(4)H arom), 7.18 (m, 4H, *o*-PAr), 7.30 (t, 1H, ^3J = 7, C(5)H arom), 7.49 (dd, 1H, ^3J = 7, $^3J_{HP}$ = 4, C(6)H arom). ^{13}C{^{1}H} NMR (δ, ppm): 45.3 (NCH_3), 55.5 (OCH_3), 62.2 (d, $^3J_{CP}$ = 19, NCH_2), 114.3 (d, $^4J_{HP}$ = 8, *m*-PAr), 127.2 (C(4) arom), 128.7 (C(5)H arom), 128.8 (d, $^2J_{CP}$ = 7, C(1)), 129.2 (d, $^3J_{CP}$ = 5, C(6)H arom), 133.4 (C(3)H arom), 135.6 (d, $^2J_{CP}$ = 21, *o*-PAr), 137.8 (d, $^1J_{CP}$ = 15, C(2)) 143.6 (d, $^1J_{CP}$ = 20, C(1) of PAr), 160.3 (*p*-PAr). ^{31}P{^{1}H} NMR (δ, ppm): –33.5. HRMS [M+H]$^+$ 380.1774 calcd for $C_{23}H_{27}NO_2P^+$, found 380.1788.

1-{2-[Bis(4-trifluoromethylphenyl)phosphino]phenyl}-*N*,*N*-dimethylmethanamine (42c). CPC **41** (19.9 mg, 0.0360 mmol) was reacted in PhMe with bis(4-trifluoromethylphenyl)phosphine (40 μL, 0.16 mmol) for 18 h at 40 °C followed by purification using preparative TLC (1:4 acetone–hexane). Complex **42c** was obtained in the amount of 18.6 mg (57% yield) as a colorless liquid. R_f = 0.41 (7:3 acetone–hexane). ^{1}H NMR (δ, ppm): 1.91 (s, 6H, N(CH_3)$_2$), 3.61 (s, 2H, NCH_2), 6.94 (dd, 1H, $^3J_{HP}$ = 4, ^3J = 8, C(3)H arom) 7.22 (td, 1H, $^3J_{HP}$ = 2, ^3J = 8, C(4)H arom), 7.31–7.38 (m, 6H, *o*-PAr and C(6)H and C(5)H arom), 7.56 (d, 4H, ^3J = 8, *m*-PAr). ^{13}C{^{1}H} NMR (δ, ppm): 44.1 (NCH_3), 63.2 (d, $^4J_{HP}$ = 14, NCH_2), 124.4 (q, $^1J_{CF}$ = 272, CF_3), 125.3 (dq, $^3J_{CF}$ = 3, $^3J_{CP}$ = 7, *m*-PAr), 128.0 (C(4) arom), 129.5 (C(5) arom), 129.8 (d, $^3J_{CP}$ = 6, C(6) arom), 130.6 (q, $^2J_{CF}$ = 32, *p*-PAr), 133.8 (d, $^2J_{CP}$ = 20, *o*-PAr), 135.0 (d, $^3J_{CP}$ = 2, C(3) arom), 135.8 (d, $^2J_{CP}$ = 15, C(1) arom), 143.6 (d, $^1J_{CP}$ = 14, C(1) of PAr), 145.3 (d, $^2J_{CP}$ = 25, C(2) arom). ^{31}P{^{1}H} NMR (δ, ppm): –30.2. HRMS [M+H]$^+$ 456.1310 calcd for $C_{23}H_{21}F_6NP^+$, found 456.1352.

(1*S*,4*S*)-1-{[Bis(4-methoxyphenyl)phosphino]methyl}-3,3-dimethylbicyclo[2.2.1]heptan-2-one *O*-Methyloxime (49b). CPC **85** (20.3 mg, 0.0315 mmol) was reacted in PhMe with bis(4-methoxyphenyl)phosphine (69.8 mg, 0.284 mmol) for 18 h at 35 °C followed by purification using preparative TLC (125:125:1 CH_2Cl_2–hexane–MeOH). Compound **49b** was obtained in the amount of 9.1 mg (42% yield) as a light yellow oil. R_f = 0.50 (1:4 acetone–hexane); $[\alpha]_D^{20}$ = +45.8° (*c* 0.490, acetone). ^{1}H NMR (δ, ppm): 1.18, 1.23 (two s, 6H, 2CH_3), 1.29 (d, 1H, $^2J_{7A,7B}$ = 10.1, H(7A)), 1.34–1.41 (m, 1H, H(6endo)), 1.48–1.51 (m, 2H, H(5endo) and H(7B)), 1.70–1.78 (m, 2H, H(4) and H(5exo)), 1.93 (tt, 1H, $^3J_{6exo,5endo}$ = $^4J_{6exo,P}$ = 2, $^2J_{6exo,6endo}$ = $^3J_{6exo,5exo}$ = 12, H(6exo)), 1.70–1.78 (m, 2H, H(4) and H(5exo)), 2.38 (dd, 1H, $^2J_{HP}$ = 3, ^2J = 15, PCH^A), 2.52 (dd, 1H, $^2J_{HP}$ = 4, ^2J = 15, PCH^B), 3.74 (s, 3H, $NOCH_3$), 3.79 (s, 6H, $ArOCH_3$), 6.86 (d, 4H, ^2J = 8, *m*-PAr), 7.36–7.44 (m, 4H, *o*-PAr). ^{13}C{^{1}H} NMR (δ, ppm): 22.9 and 23.5 (two CH_3), 25.3 (C(5)), 31.5 (PCH_2), 33.4 (d, $^3J_{CP}$ = 9, C(6)), 41.5 (d, $^3J_{CP}$ = 8, C(7)), 44.7 (C(3)), 48.6 (C(4)), 52.9 (d, $^2J_{CP}$ = 16, C(1)), 55.5 ($ArOCH_3$), 61.6 ($NOCH_3$), 114.3 (t, $^3J_{CP}$ = 7, *m*-PAr), 131.3 (d, $^1J_{CP}$ = 10, *p*-PAr^A), 131.4 (d, $^1J_{CP}$ = 10, *p*-PAr^B), 134.4 (d, $^2J_{CP}$ = 20, *o*-PAr^A), 134.6 (d, $^2J_{CP}$ = 20, *o*-PAr^B), 160.2 (d, $^1J_{CP}$ = 11, C(1) of PAr), 172.5 (C=N). ^{31}P{^{1}H} NMR (δ, ppm): –41.5. HRMS $[M+H]^+$ 426.2192 calcd for $C_{25}H_{33}NO_3P^+$, found 426.2274.

(1*S*,4*S*)-1-{Bis(4-trifluoromethylphenyl)phosphino)methyl}-3,3-dimethylbicyclo[2.2.1] heptan-2-one *O*-Methyloxime (49c). CPC **85** (22.8 mg, 0.0354 mmol) was reacted in CH_2Cl_2 with bis(4-trifluoromethylphenyl)phosphine (102.6 mg, 0.318 mmol) for 18 h at 35 °C followed by purification using preparative TLC (125:125:1 CH_2Cl_2–hexane–acetone). Compound **49c** was obtained in the amount of 13.0 mg (53% yield) as a colorless oil. R_f = 0.50 (1:1 CH_2Cl_2–hexane); $[\alpha]_D^{20}$ = +35.3° (*c* 0.305, acetone).

^{1}H NMR (δ, ppm): 1.21, 1.26 (two s, 6H, 2CH_3), 1.27 (d, 1H, $^{2}J_{7A,7B}$ = 10, H(7A)), 1.45–1.57 (m, 2H, H(5endo) and H(6endo)), 1.65 (dd, 1H, $^{4}J_{HP}$ = 1, $^{2}J_{7A,7B}$ = 10, H(7B)), 1.75–1.86 (m, 3H, H(4), H(5exo) and H(6exo)), 2.47 (dd, $^{2}J_{HP}$ = 4, ^{2}J = 15, PCH^{A}), 2.63 (dd, $^{2}J_{H,P}$ = 4, ^{2}J = 15, PCH^{B}), 3.70 (s, 3H, $NOCH_3$), 7.53–7.61 (m, 8H, *o*-PAr and *m*-PAr). ^{13}C{^{1}H} NMR (δ, ppm): 22.8 and 23.4 (two CH_3), 25.3 (C(5)), 31.3 (d, $^{1}J_{CP}$ = 8, PCH_2), 34.1 (d, $^{1}J_{CP}$ = 9, C(6)), 41.7 (d, $^{3}J_{CP}$ = 9, C(7)), 44.7 (C(3)), 48.7 (C(4)), 52.9 (C(1)), 61.6 ($NOCH_3$), 124.4 (qd, $^{5}J_{CP}$ = 2, $^{1}J_{CF}$ = 273, CF_3), 125.5 (dq, $^{3}J_{CF}$ = 3, $^{3}J_{CP}$ = 12, *m*-PAr), 131.0 (qd, $^{4}J_{CP}$ = 3, $^{2}J_{CF}$ = 32, *p*-PAr), 133.4 and 133.6 (two d, $^{2}J_{CP}$ = 10, *o*-PAr), 144.8 (dd, $^{4}J_{CF}$ = 2, $^{2}J_{CP}$ = 16, C(1) of PAr), 171.5 (C=N). ^{31}P{^{1}H} NMR (δ, ppm): –35.5. HRMS $[M+NH_4]^+$ 518.1916 calcd for $C_{25}H_{30}F_6N_2OP^+$, found 518.1899.

(1*S*,4*S*)-1-{[bis(2,4,6-trimethylphenyl)oxophosphino]methyl}-3,3-dimethylbicyclo[2.2.1] heptan-2-one *O*-Methyloxime (49d'). CPC **85** (17.0 mg, 0.0264 mmol) was reacted in CH_2Cl_2 with bis(2,4,6-trimethylphenyl)phosphine (64.0 mg, 0.237 mmol) for 96 h at 35 °C followed by purification using preparative TLC (125:125:1 CH_2Cl_2–hexane–acetone). Compound **49d'** was obtained in the amount of 9.0 mg (32% yield) as a colorless oil. R_f = 0.47 (1:1 CH_2Cl_2–hexane); $[\alpha]_D^{21}$ = –31.6° (*c* 0.460, acetone). ^{1}H NMR (δ, ppm): 1.18 and 1.24 (two s, 6H, 2CH_3), 1.33–1.41 (m, 1H, H(6endo)), 1.49–1.60 (m, 3H, H(7), and H(5endo)), 1.72–1.81 (m, 2H, H(4) and H(5exo)), 1.93 (tt, 1H, $^{2}J_{6exo,6endo}$ = $^{3}J_{6exo,5exo}$ = 12, $^{3}J_{6exo,5endo}$ = $^{4}J_{6exo,P}$ = 3, H(6exo)), 2.21 and 2.22 (two s, 6H, 2 *p*-CH_3Ar), 2.32 and 2.36 (two s, 12H, 4 *o*-CH_3Ar), 2.73 (dd, 1H, ^{2}J = 15, $^{2}J_{HP}$ = 4, PCH^{A}), 2.96 (dd, 1H, ^{2}J = 15, $^{2}J_{HP}$ = 3, PCH^{B}), 3.67 (s, 3H, $NOCH_3$), 6.76 (dd, 4H, ^{2}J = 9, $^{4}J_{HP}$ = 2, *m*-PAr). ^{13}C{^{1}H} NMR (δ, ppm): 21.1 and 21.2 (*p*-CH_3Ar), 22.9 (CH_3^{B}), 23.5 (d, $^{4}J_{CP}$ = 14, *o*-CH_3Ar^{A}), 23.5 (CH_3^{A}), 23.8 (d, $^{4}J_{CP}$ = 14, *o*-CH_3Ar^{B}), 25.5 (C(5)), 28.6 (d, $^{2}J_{CP}$ = 15,

PCH_2), 32.6 (d, $^3J_{CP}$ = 11, C(6)), 40.8 (d, $^3J_{CP}$ = 9, C(7)), 44.7 (d, $^4J_{CP}$ = 2, C(3)), 48.3 (C(4)), 53.9 (d, $^2J_{CP}$ = 23, C(1)), 61.5 ($NOCH_3$), 130.1 and 130.3 (two d, $^3J_{CP}$ = 3, *m*-PAr), 135.0 (t, $^4J_{CP}$ = 22, *p*-PAr), 141.9 and 142.7 (two d, $^2J_{CP}$ = 15, *o*-PAr), 137.2 and 137.7 (C(1) of PAr), 172.5 (d, $^3J_{CP}$ = 6, C=N). $^{31}P\{^1H\}$ NMR (δ, ppm): –45.7. HRMS $[M+H]^+$ 466.2869 calcd for $C_{29}H_{41}NO_2P^+$, found 466.2889.

(1*S*,4*S*)-1-[(*tert*-butylphenylphosphino)methyl]-3,3-dimethylbicyclo[2.2.1]heptan-2-one *O*-Methyloxime (49f). CPC **85** (17.0 mg, 0.0264 mmol) was reacted in CH_2Cl_2 with *tert*-butylphenylphosphine (40.0 mg, 0.241 mmol) for 96 h at 35 °C followed by purification using preparative TLC (1:1 CH_2Cl_2–hexane). A single isomer of compound **49f** was obtained in the amount of 2.2 mg (12% yield) as a colorless oil. R_f = 0.43 (1:1 CH_2Cl_2–hexane); $[\alpha]_D^{21}$ = +126° (*c* 0.205, acetone). ^1H NMR (δ, ppm): 0.99 (d, 9H, $^1J_{CP}$ = 12, $C(CH_3)_3$), 1.20 and 1.22 (two s, 6H, $2CH_3$), 1.22–1.38 (m, 2H, H(6endo) and H(7A)), 1.43 (tt, 1H, $^3J_{5(endo),6(exo)} = {}^3J_{5(endo),4}$ = 4, $^2J = {}^3J_{5(endo),6(endo)}$ = 12, H(5endo)), 1.54 (td, 1H, $^3J_{5(endo),6(exo)}$ = 4, $^2J = {}^3J_{5(endo),6(endo)}$ = 12, H(6exo)), 1.59 (br s, 1H, H(7B)), 1.69 (br s, 2H, H(4) and H(5exo)), 2.04 (d, 1H, ^2J = 15, $PCH_2{}^A$), 2.04 (dd, 1H, $^2J_{HP}$ = 7, ^2J = 15, $PCH_2{}^B$), 3.76 (s, 3H, $NOCH_3$), 7.32–7.37 (m, 3H, *m*- and *p*-PAr), 7.56–7.65 (m, 2H, *o*-PAr). $^{13}C\{^1H\}$ NMR (δ, ppm): 22.5 (d, $^1J_{CP}$ = 17, $\underline{C}(CH_3)_3$), 22.9 and 23.4 (two CH_3), 25.3 (C(5)), 27.7 (d, $^2J_{CP}$ = 13, $C(\underline{C}H_3)_3$), 29.3 (d, $^1J_{CP}$ = 11, PCH_2), 34.7 (d, $^3J_{CP}$ = 7, C(6)), 41.4 (d, $^3J_{CP}$ = 9, C(7)), 44.7 (C(3)), 48.4 (C(4)), 52.9 (d, $^2J_{CP}$ = 19, C(1)), 61.6 ($NOCH_3$), 128.0 (d, $^3J_{CP}$ = 7, *m*-PAr), 129.1 (br s, overlapping *p*-PAr and C(1) of PAr), 134.6 (d, $^2J_{CP}$ = 20, *o*-PAr), 171.6 (C=N). $^{31}P\{^1H\}$ NMR (δ, ppm): –18.6. HRMS $[M+H]^+$ 346.2294 calcd for $C_{21}H_{33}NOP^+$, found 346.2303.

Chloro-{[2-(*N*,*N*-dimethylamino)methyl]phenyl-*C*,*N*}[bis(2,4,6-trimethylphenyl)phosphine-*P*]palladium(II) (90d). CPC **41** (20.2 mg, 0.0366 mmol) was reacted in CH_2Cl_2 with bis(2,4,6-trimethylphenyl)phosphine (10.0 mg, 0.0370 mmol) for 0.5 h at rt followed by purification using preparative TLC (1:4 acetone–hexane). Complex **90d** was obtained in the amount of 35.8 mg (90% yield) as a white solid. R_f = 0.22 (1:4 acetone-hexane); m.p. 152–153 °C (dec.). ^{1}H NMR (δ, ppm): 2.27 (s, 6H, *p*-CH_3Ar), 2.51 (s, 12H, *o*-CH_3Ar), 2.82 (s, 6H, $^4J_{HP}$ = 2, NCH_3), 3.98 (s, 2H, NCH_2), 6.32 (d, 1H, $^1J_{HP}$ = 382, HP), 6.60 (t, 1H, ^3J = $^3J_{HP}$ = 8, C(6)H arom), 6.77 (br t, 1H, ^3J = 8, C(5)H arom), 6.87 (d, 4H, $^4J_{HP}$ = 3, *m*-PAr), 6.98 (br t, 1H, ^3J = 8, C(4)H arom), 7.06 (br d, 1H, ^3J = 8, C(3)H arom). ^{13}C{^{1}H} NMR (δ, ppm): 21.5 (*p*-CH_3Ar), 23.9 (d, $^3J_{CP}$ = 10, *o*-CH_3Ar), 51.0 (d, $^3J_{CP}$ = 2, NCH_3), 73.2 (d, $^3J_{CP}$ = 3, CH_2), 122.8 (d, $^1J_{CP}$ = 49, C(1) of PAr), 123.1 (C(3) arom), 124.7 (C(4) arom), 126.7 (d, $^4J_{CP}$ = 7, C(5) arom), 130.5 (d, $^3J_{CP}$ = 8, *m*-PAr), 133.3 (d, $^4J_{CP}$ = 17, C(6) arom), 140.8 (d, $^4J_{CP}$ = 2, *p*-PAr), 142.8 (d, $^3J_{CP}$ = 8, *o*-PAr), 148.9 and 150.6 (two d, J_{CP} = 2 and 3, C(2) arom and PdC(1) arom). ^{31}P{^{1}H} NMR (δ, ppm): –47.6; ^{31}P NMR (δ, ppm): –47.6 (d, $^1J_{HP}$ = 382). Anal. calcd for $C_{27}H_{35}ClNPPd$: C, 59.35; H, 6.46; N, 2.56%. Found: C, 59.05; H, 6.40; N, 2.54%.

Chloro-{[2-(*N*,*N*-dimethylamino)methyl]phenyl-*C*,*N*}(di-1-adamantylphosphine-*P*) palladium (II) (90e). CPC **41** (17.2 mg, 0.0312 mmol) was reacted in CH_2Cl_2 with di-1-adamantylphosphine (18.8 mg, 0.624 mmol) for 0.5 h at rt followed by purification using preparative TLC (1:4 acetone–hexane). Complex **90e** was obtained in the amount of 32.2 mg (90% yield) as a white solid. R_f = 0.38 (1:4 acetone-hexane); m.p. 198–199 °C (dec.). ^{1}H NMR (δ, ppm): 1.71 and 1.78 (two d, 12H, ^2J = 12, C(4)H_2 of Ad), 2.00 (s, 6H, C(3)H of Ad), 2.23 and 2.35 (two d, 12H, ^2J = 12, C(2)H_2 of Ad), 2.71 (s, 6H, NCH_3), 3.73 (d,

1H, $^{1}J_{HP}$ = 342, HP), 3.92 (s, 2H, NCH_2), 6.98–7.03 (m, 2H, C(5)H and C(6)H arom), 7.03–7.08 (m, 1H, C(4)H arom), 7.22–7.27 (m, 1H, C(3)H arom). $^{13}C\{^{1}H\}$ NMR (δ, ppm): 29.0 (d, $^{3}J_{CP}$ = 9, C(3) of Ad), 36.7 (C(4) of Ad), 39.0 (d, $^{1}J_{CP}$ = 20, C(1) of Ad), 43.0 (C(2) of Ad), 50.0 (d, $^{3}J_{CP}$ = 2, NCH_3), 72.9 (d, $^{3}J_{CP}$ = 3, NCH_2), 123.4 (C(4) arom), 124.4 (C(3) arom), 125.7 (d, $^{4}J_{CP}$ = 6, C(5) arom), 135.7 (d, $^{3}J_{CP}$ = 15, C(6) arom), 149.1 and 149.5 (s and d, J_{CP} = 2, C(2) arom and PdC(1) arom). $^{31}P\{^{1}H\}$ NMR (δ, ppm): 71.3; ^{31}P NMR (δ, ppm): 71.3 (d, $^{1}J_{HP}$ = 342). Anal. calcd for $C_{29}H_{43}ClNPPd$: C, 60.21; H, 7.49; N, 2.42%. Found: C, 60.38; H, 7.43; N, 2.42%.

***μ*-Chloro-*μ*-[bis(4-trifluoromethylphenyl)phosphido]bis{[2-(*N*,*N*-dimethylamino)methyl] phenyl-*C*,*N*}dipalladium(II) (91c).** CPC **41** (13.6 mg, 0.0246 mmol) was reacted in PhMe with bis(4-trifluoromethylphenyl)phosphine (54 μL, 0.22 mmol) for 18 h at 40 °C followed by purification using preparative TLC (1:4 acetone–hexane). Complex **91c** was obtained in the amount of 6.0 mg (29% yield) as a yellow solid. R_f = 0.38 (1:9 acetone-hexane); m.p. 168–170 °C (dec.). ^{1}H NMR (δ, ppm): 2.69 (s, 6H, NCH_3), 3.89 (s, 4H, NCH_2), 6.31 (dd, 2H, $^{4}J_{HP}$ = 4, ^{3}J = 8, C(6)H arom), 6.51 (t, 2H, ^{3}J = 8, C(5)H arom), 6.83 (t, 2H, ^{3}J = 8, C(4)H arom), 6.93 (d, 2H, ^{3}J = 8, C(3) arom), 7.50 (d, 4H, ^{3}J = 8, *m*-PAr), 7.99 (dd, 4H, ^{3}J = 8, $^{3}J_{HP}$ = 11, *o*-PAr). $^{13}C\{^{1}H\}$ NMR (δ, ppm): 49.8 (NCH_3), 71.3 (d, $^{3}J_{CP}$ = 2, NCH_2), 123.0 (C(3) arom), 124.1 (C(4) arom), 124.4 (q, $^{1}J_{CF}$ = 271, CF_3), 125.0 (dq, $^{3}J_{CF}$ = 4, $^{3}J_{CP}$ = 11, *m*-PAr), 125.9 (d, $^{4}J_{CP}$ = 5, C(5) arom), 131.0 (qd, $^{4}J_{CP}$ = 2, $^{3}J_{CF}$ = 32, *p*-PAr), 135.8 (d, $^{2}J_{CP}$ = 13, *o*-PAr), 137.5 (d, $^{3}J_{CP}$ = 9, C(6) arom), 140.8 (d, $^{1}J_{CP}$ = 24, C(1) of PAr), 147.8 and 148.7 (two d, J_{CP} = 2 and 3, C(2) arom and PdC(1) arom). $^{31}P\{^{1}H\}$ NMR (δ, ppm): 19.9. Anal. calcd for $C_{36}H_{46}ClN_2PPd_2$: C, 45.87; H, 3.85; N, 3.34%. Found: C, 46.06; H, 4.00; N, 3.07%.

***μ*-Chloro-*μ*-[bis(2,4,6-trimethylphenyl)phosphido]bis{[2-(*N*,*N*-dimethylamino)methyl] phenyl-*C*,*N*}dipalladium(II) (91d).** CPC **41** (41.3 mg, 0.0748 mmol) was reacted in CH_2Cl_2 with bis(2,4,6-trimethylphenyl)phosphine (21.0 mg, 0.777 mmol) for 18 h at 35 °C followed by purification using preparative TLC (1:4 acetone–hexane). Complex **91d** was obtained in the amount of 57.6 mg (98% yield) as a yellow solid. R_f = 0.58 (1:7 acetone-hexane); m.p. 169–170 °C (dec.). ^{1}H NMR (δ, ppm): 2.22 (s, 6H, *p*-CH_3Ar), 2.68 (s, 12H, *o*-CH_3Ar), 2.72 (s, 6H, NCH_3^A), 2.73 (s, 6H, NCH_3^B), 3.88 (s, 4H, NCH_2), 6.45–6.51 (m, 4H, C(6)H and C(5)H arom), 6.73 (d, 4H, $^3J_{HP}$ = 3, *m*-PAr), 6.80 (t, 2H, ^3J = 7, C(4)H arom), 6.86 (d, 2H, ^3J = 7, C(3) arom). ^{13}C{^{1}H} NMR (δ, ppm): 21.3 (*p*-CH_3Ar), 27.5 (d, $^3J_{CP}$ = 12, *o*-CH_3Ar), 50.7 (NCH_3), 71.7 (d, $^3J_{CP}$ = 2, CH_2), 121.6 (C(3) arom), 123.4 (C(4) arom), 125.7 (d, $^4J_{CP}$ = 5, C(5) arom), 130.7 (d, $^3J_{CP}$ = 7, *m*-PAr), 131.0 (br d, $^1J_{CP}$ = 22, C(1) of PAr), 135.8 (d, $^3J_{CP}$ = 7, C(6) arom), 138.2 (d, $^4J_{CP}$ = 3, *p*-PAr), 143.6 (d, $^2J_{CP}$ = 8, *o*-PAr), 147.8 and 153.4 (two d, J_{CP} = 3 and 6, C(2) arom and PdC(1) arom). ^{31}P{^{1}H} NMR (δ, ppm): –12.1. Anal. calcd for $C_{36}H_{46}ClN_2PPd_2$: C, 55.01; H, 5.90; N, 3.56%. Found: C, 55.74; H, 5.94; N, 3.65%.

(1*S*,4*S*)-Chloro-[(2-methoxyimino-3,3-dimethylbicyclo[2.2.1]heptyl)methyl-*C*,*N*][bis(2,4,6-trimethylphenyl)phosphine-*P*]palladium(II) (92d). CPC **85** (20.2 mg, 0.0314 mmol) was reacted in CH_2Cl_2 with bis(2,4,6-trimethylphenyl)phosphine (17.0 mg, 0.0629 mmol) for 0.5 h at rt followed by purification using preparative TLC (1:4 acetone–hexane). Compound **92d** was obtained in the amount of 25.5 mg (69% yield) as a white solid. R_f = 0.50 (2:3 acetone–hexane); m.p. 169–171 °C (dec.); $[\alpha]_D^{20}$ = –292° (*c* 2.01, acetone). ^{1}H NMR (δ, ppm): 0.78 (t, ^2J = $^3J_{HP}$ = 10, $PdCH^A$), 1.21 (d, 1H, $^2J_{7A,7B}$ = 10, H(7A)), 1.24 and 1.25 (two s, 6H, two CH_3), 1.47 (td, 1H, $^3J_{5(exo),6(endo)}$ = 3, ^2J =

$^{3}J_{5(endo),6(endo)}$ = 12, H(6endo)), 1.55 (tt, 1H, $^{3}J_{5(endo),6(exo)}$ = $^{3}J_{5(endo),4}$ = 4, ^{2}J = $^{3}J_{5(endo),6(endo)}$ = 12, H(5endo)), 1.72 (d, 1H, $^{2}J_{7A,7B}$ = 10, H(7B)), 1.78–1.91 (m, 2H, H(5exo) and H(6exo)), 2.01 (d, 1H, $^{3}J_{5(endo),4}$ = 4, H(4)), 2.17 (d, ^{2}J = 10, PdCH^{B}), 2.24 (s, 6H, *p*-CH_3Ar), 2.46 and 2.49 (two s, 12H, *o*-CH_3Ar), 4.07 (s, 3H, $NOCH_3$), 6.47, (d, 1H, $^{1}J_{HP}$ = 389, HP), 6.82 (s, 4H, $^{4}J_{HP}$ = 3, *m*-PAr). $^{13}C\{^{1}H\}$ NMR (δ, ppm): 21.4 (d, $^{5}J_{CP}$ = 2, *p*-CH_3Ar), 22.7 and 23.3 (two CH_3), 23.4 and 23.6 (two d, $^{3}J_{CP}$ = 10, *o*-CH_3Ar), 25.4 (C(5)), 30.0 ($PdCH_2$), 34.7 (C(6)), 43.2 (C(7)), 44.1 (C(3)), 52.9 (C(4)), 63.2 ($NOCH_3$), 64.3 (C(1)), 123.0 and 123.5 (two d, $^{2}J_{CP}$ = 50, C(1) of PAr), 130.2 and 130.3 (two d, $^{3}J_{CP}$ = 6, *m*-PAr), 140.3 (d, $^{4}J_{CP}$ = 2, *p*-PAr), 142.0 and 142.1 (two d, $^{2}J_{CP}$ = 8, *o*-PAr), 195.8 (d, $^{3}J_{CP}$ = 2, C=N). $^{31}P\{^{1}H\}$ NMR (δ, ppm): –54.6. ^{31}P NMR (δ, ppm): –54.6 (d, $^{1}J_{HP}$ = 389). Anal. calcd for $C_{29}H_{41}ClNOPPd$: C, 58.79; H, 6.98; N, 2.36%. Found: C, 58.67; H, 7.12; N, 2.31%.

(1*S*,4*S*)-Chloro-[(2-methoxyimino-3,3-dimethylbicyclo[2.2.1]heptyl)methyl-*C*,*N*](di-1-adamantylphosphine-*P*)palladium(II) (92e). CPC **85** (15.1 mg, 0.0234 mmol) was reacted in PhMe with di-1-adamantylphosphine (14.2 mg, 0.0463 mmol) for 0.5 h at rt followed by purification using preparative TLC (1:4 acetone–hexane). Compound **92e** was obtained in the amount of 25.1 mg (86% yield) as a white solid. R_f = 0.45 (1:4 acetone–hexane); m.p. 168–170 °C (dec.); $[\alpha]_D^{21}$ = –199° (*c* 1.10, acetone). ^{1}H NMR data for two isomers in a ratio of 1:4 (δ, ppm; signals assigned to the minor isomer are marked with an asterisk): 1.15 (t, ^{2}J = $^{3}J_{HP}$ = 11, $PdCH_2^{A}$), 1.24, 1.25, 1.26*, and 1.27* (four overlapping s, two CH_3), 1.33 and 1.40* (two d, ^{2}J = 11, C(7)H^{A}), 1.58–1.92, 1.96–2.12 and 2.13–2.33 (three complex m, 15H of Ad, $PdCH_2^{B}$, C(4)H, C(5)H_2, C(6)H_2, and C(7)H^{B}), 3.36 (d, $^{1}J_{HP}$ = 339, HP), 4.04* and 4.05 (two s, 3H, $NOCH_3$), 4.06* (d, $^{1}J_{HP}$ = 359, HP). $^{13}C\{^{1}H\}$ NMR (δ, ppm): 15.9* (d, $^{2}J_{CP}$ = 3.8, PdC), 22.6*, 22.7, 23.3*, and 23.4 (four s, two CH_3), 25.5

and 25.6* (two s, C(5)), 26.5 (PdC), 28.8*, 28.9*, 28.95, and 29.03 (four d, $^{3}J_{CP}$ = 9* and 4, C(3) of Ad), 34.9* and 35.4 (two s, (C(6)), 36.7* and 36.8 (two s, C(4) of Ad), 38.3, 38.4*, 38.5*, and 38.7 (four d, $^{1}J_{CP}$ = 19* and 20, C(1) of Ad), 42.5*, 42.6, 42.7, and 42.9* (four s, C(2) of Ad), 43.4 and 43.9* (two s, C(7)), 43.8* and 44.0 (two s, C(3)), 52.8 and 52.8* (two overlapping s, C(4)), 63.1* and 63.2 (two s, $NOCH_3$), 64.3 and 64.8* (two s, C(1)), 193.8* and 194.8 (d, $^{3}J_{CP}$ = 2, C=N). $^{31}P\{^{1}H\}$ NMR (δ, ppm): 49.5* and 51.7; ^{31}P NMR (δ, ppm): 49.5* and 51.7 (two d, $^{1}J_{HP}$ = 359* and 339). Anal. calcd for $C_{31}H_{49}ClNOPPd$: C, 59.61; H, 7.91; N, 2.24%. Found: C, 59.58; H, 8.06; N, 2.13%.

(1*S*,4*S*)-Chloro-[(2-methoxyimino-3,3-dimethylbicyclo[2.2.1]heptyl)methyl-*C,N*](*tert*-butylphenylphosphine-*P*)palladium(II) (92f). CPC **85** (25.8 mg, 0.0400 mmol) was reacted in CH_2Cl_2 with *tert*-butylphenylphosphine (29.9 mg, 0.1799 mmol) for 0.5 h at rt followed by purification using preparative TLC (1:4 acetone–hexane). Two diastereomers of **92f** were obtained in the amount of 20.7 mg (77% yield) as a transparent colorless solid in a ratio of 5:4. R_f = 0.45 (2:3 acetone–hexane); m.p. 102–110 °C; $[\alpha]_D^{20}$ = –382° (*c* 0.290, acetone). ^{1}H NMR data for a 5:4 mixture of two diastereomers (δ, ppm; signals assigned to the minor isomer are marked with an asterisk): 1.22*, 1.23, 1.24*, and 1.25 (four s, two CH_3), 1.26 (m, *$PdCH^{A}$), 1.31 (d, 9H, $^{3}J_{HP}$ = 16, $C(CH_3)_3$), 1.29–1.46 (overlapping m, H(7A), H(5endo), and $PdCH^{A}$), 1.51–1.97 (m, H (5exo), H(6exo), H(7B), and H(6endo)), 2.02* and 2.06 (two d, ^{3}J = 4, H(4)), 2.26 and 2.29* (two d, ^{2}J = 10, $PdCH^{B}$), 4.02 and 4.05* (two s, $NOCH_3$), 4.70 and 4.71* (two d, $^{1}J_{HP}$ = 357, HP), 7.37–7.49 (m, *o*- and *p*-PAr), 7.91* and 8.00 (two ddd, $^{4}J_{HP}$ = 1, ^{3}J = 7, ^{3}J = 10.2, *m*-PAr). $^{13}C\{^{1}H\}$ NMR data for a 5:4 mixture of two diastereomers (δ, ppm; signals assigned to the minor isomer are marked with an asterisk): 22.6* and 22.7 (CH_3), 23.3 (two overlapping s, CH_3), 25.4* and

25.5 (C(5)), 27.3* and 27.8 (PdC), 29.0* and 29.1 (two d, $^{2}J_{CP}$ = 5, PC($\underline{C}H_3)_3$), 32.5* and 32.8 (two d, $^{1}J_{CP}$ = 29, P$\underline{C}(CH_3)_3$), 34.9* and 35.3 (C(6)), 43.4 (two overlapping s, C(7)), 44.1 two overlapping d, $^{4}J_{CP}$ = 3, C(3)), 52.8* and 52.9 (C(4)), 63.2 (two overlapping s, $NOCH_3$), 64.2* and 64.3 (C(1)), 128.2* and 128.4 (two d, $^{1}J_{CP}$ = 31, C(1) of PPh), 128.68* and 128.70 (two d, $^{3}J_{CP}$ = 9, *o*-PPh), 130.9* and 131.0 (two d, $^{4}J_{CP}$ = 3, *p*-PAr), 135.2* and 135.4 (two d, $^{2}J_{CP}$ = 9, *m*-PAr), 196.1 (two overlapping s, C=N). $^{31}P\{^{1}H\}$ NMR (δ, ppm): 27.3* and 27.4; ^{31}P NMR (δ, ppm): 27.3* and 27.4 (two overlapping d, $^{1}J_{HP}$ = 357). Anal. calcd for $C_{21}H_{33}ClNOPPd$: C, 51.65; H, 6.81; N, 2.87%. Found: C, 51.41; H, 6.74; N, 2.75%.

(1*S*,4*S*)-*μ*-Chloro-*μ*-[bis(2,4,6-trimethylphenyl)phosphido]bis{[(2-methoxyimino-3,3-dimethylbicyclo[2.2.1]heptyl)methyl-*C*,*N*]dipalladium(II) (93d). CPC **85** (38.8 mg, 0.0602 mmol) was reacted in CH_2Cl_2 with bios(2,4,6-trimethylphenyl)phosphine (16.3 mg, 0.0603 mmol) for 18 h at 35 °C followed by purification using preparative TLC (1:4 acetone–hexane). Compound **93d** was obtained in the amount of 36.3 mg (69% yield) as a yellow solid. R_f = 0.66 (1:4 acetone–hexane); m.p. 181–182 °C (dec.); $[\alpha]_D^{20}$ = –66.9° (*c* 0.715, acetone). ^{1}H NMR (δ, ppm): 1.03 (dd, 2H, $^{2}J_{HP}$ = 5, ^{2}J = 10, $PdCH^{A}$), 1.16 (s, 6H, two CH_3), 1.21 (s and overlapping m, 8H, two CH_3 and H(7A)), 1.49–1.65 (m, 8H, H(7B), H(5endo) and $PdCH^{B}$), 1.79 (t, 2H, ^{2}J = 10, H(5exo)), 1.87–1.94 (m, 4H, H(4) and H(6exo)), 2.23 (s, 6H, *p*-CH_3Ar), 2.70 (s, 12H, *o*-CH_3Ar), 3.90 (s, 6H, OCH_3), 6.77 (s, 4H, *m*-Ar). $^{13}C\{^{1}H\}$ NMR (δ, ppm): 21.2 (*p*-CH_3Ar), 22.7 and 23.3 (two CH_3), 25.4 ($^{2}J_{CP}$ = 3, $PdCH_2$), 25.6 (C(5)), 26.6 (*o*-CH_3Ar), 34.4 (C(6)), 43.5 (C(7)), 44.0 (C(3)), 52.2 (C(4)), 62.6 ($NOCH_3$), 64.3 (C(1)), 130.0 (d, $^{3}J_{CP}$ = 7, *m*-PAr), 133.8 (d, $^{1}J_{CP}$ = 24, C(1) of PAr), 136.5 (d, $^{4}J_{CP}$ = 2, *p*-PAr), 140.9 (d, $^{2}J_{CP}$ = 8, *o*-PAr), 193.0 (C=N). $^{31}P\{^{1}H\}$ NMR (δ, ppm):

–44.7. Anal. calcd for $C_{40}H_{58}ClN_2O_2PPd_2$: C, 54.71; H, 6.66; N, 3.19%. Found: C, 54.45; H, 6.46; N, 3.28%.

(1*S*,4*S*)-*μ*-Chloro-*μ*-(di-1-adamantylphosphido)bis[(2-methoxyimino-3,3-dimethylbicyclo[2.2.1]heptyl)methyl-*C*,*N*]dipalladium(II) (93e). CPC **85** (19.8 mg, 0.0307 mmol) was reacted in CH_2Cl_2 with di-1-adamantylphosphine (9.3 mg, 0.031 mmol) for 18 h at 35 °C followed by purification with preparative TLC (1:4 acetone–hexane). Compound **93e** was obtained in the amount of 18.5 mg (66% yield) as a yellow solid. R_f = 0.44 (1:1 CH_2Cl_2–hexane); m.p. 200–201 °C (dec.); $[\alpha]_D^{20}$ = –409° (*c* 0.215, acetone). ^{1}H NMR (δ, ppm): 1.19 and 1.22 (two s, 12H, 4CH_3), 1.36 (d, 2H, $^2J_{7A,7B}$ = 10, H(7A)), 1.59 (tt, 2H, $^3J_{5endo,6exo}$ = $^3J_{5endo,4}$ = 5 and ^2J = $^3J_{5endo,6endo}$ = 12, H(5endo)), 1.65–1.81 (m, 18H, H(7B), H(6endo), C(4)H_2 of Ad, and PdCH^A), 1.82 (overlapping tt, 2H, $^3J_{5exo,6endo}$ = $^3J_{HP}$ = 3 and ^2J = $^3J_{5exo,6exo}$ = 12, H(5exo)), 1.87–1.93 (m, 2H, H(6exo)), 1.96 (s, 8H, H(4) and C(3)H of Ad), 2.07 (dd, 2H, $^3J_{HP}$ = 3 and ^2J = 10, PdCH^B), 2.31 and 2.4 (two d, 12H, ^2J = 12, 2C(2)H_2 of Ad), 3.90 (s, 6H, OCH_3). ^{13}C{^{1}H} NMR (δ, ppm): 15.7 (d, $^1J_{CP}$ = 2, PdC), 22.7 and 23.5 (two CH_3), 25.7 (C(5)), 29.6 (d, $^3J_{CP}$ = 9, C(3) of Ad), 34.4 (C(6)), 37.4 (C(4) of Ad), 42.2 and 43.4 (d and s, J_{CP} = 4, C(1) of Ad and C(3)), 44.1 (overlapping signals, C(2) of Ad and C(7)), 52.1 (C(4)), 62.4 (NOCH_3), 64.6 (C(1)), 191.0 (C=N). ^{31}P{^{1}H} NMR (δ, ppm): 70.5. Anal. calcd for $C_{42}H_{66}ClN_2O_2PPd_2$: C, 55.42; H, 7.31; N, 3.08%. Found: C, 55.25; H, 7.28; N, 3.00%.

(1*S*,4*S*)-*μ*-Chloro-*μ*-(*tert*-butylphenylphosphido)bis[(2-methoxyimino-3,3-dimethylbicyclo[2.2.1]heptyl)methyl-*C*,*N*]dipalladium(II) (93f) and **(1*S*,4*S*)-di[*μ*-chloro-*μ*-(*tert*-butylphenylphosphido)]bis[(2-methoxyimino-3,3-dimethylbicyclo[2.2.1]heptyl)methyl-*C*,*N*]tripalladium(II) (94f).** CPC **85** (34.8 mg,

0.0540 mmol) was reacted in PhMe with HP*t*-BuPh (9.0 mg, 0.0540 mmol) for 18 h at 40 °C followed by purification using preparative TLC (1:1 CH_2Cl_2–hexane). Compounds **93f** and **94f** were obtained in a ratio of 10:1 in the total amount of 19.2 mg (46% yield) as a light yellow solid. Data for the 10:1 mixture of **93f** and **94f**: R_f = 0.44 (1:1 CH_2Cl_2–hexane); m.p. 208–209 (dec.); $[\alpha]_D^{21}$ = –507° (*c* 0.775, acetone). ^{1}H NMR (δ, ppm; data for complex **94f** are indicated with an asterisk): 0.57 (dd, 1H, $^3J_{HP}$ = 6, ^2J = 9, PdCH^{A1}), 0.97 (dd, 1H, $^3J_{HP}$ = 4, ^2J = 10, PdCH^{A2}), 1.08–1.32 (m, 15H, CH_3, H6(endo), H(7A)), 1.40–1.62 (m, 8H, 2 H(7B), 2 H(5endo), H(6endo), PdCH^B), 1.65 (d, 9H, $^3J_{HP}$ = 15, C(CH_3)$_3$), 1.70-1.81 (m, 4H, 2 H(6exo) and 2 H(5exo)), 1.88 (s, 2H, H(4)), 2.08 (dd, 2H, ^2J = 9, PdCH^{B1}), 3.93, 395 and 3.97* (two s, 6H, $NOCH_3$), 7.15 (t, 1H, ^3J = ^3J = 7, *p*-PPh), 7.22 (t, 2H, ^3J = ^3J = 7, *m*-PPh), 7.77* and 7.89 (two t, 2H, ^3J = $^3J_{HP}$ = 7, *o*-PPh). ^{13}C{^{1}H} NMR (δ, ppm; data for complex **94f** are indicated with an asterisk; A and B are two non-equivalent cyclopalladated ligands in **93f**): 22.4, 22.5, and 22.9 (three s, CH_3), 23.0 (two overlapping s, CH_3 and PdCH_2^A), 24.6 (PdCH_2^B), 25.4 and 25.5 (two s, C(5)), 32.0 and 32.5* (two d, $^2J_{CP}$ = 7, PC($\underline{C}H_3$)$_3$), 34.3 (C(6)^A), 34.60 and 34.61* (d, $^1J_{CP}$ = 14, P$\underline{C}$(CH_3)$_3$), 35.39* (C(6)*), 35.42 (C(6)^B), 43.3 and 43.5 (two s, C(7)^A and C(7)^B), 43.4* (s, C(7)*), 43.80 (s, C(3)*), 43.82 and 43.90 (two s, (C(3)^A and C(3)^B), 51.96 (s, C(4)^A), 52.03 (two overlapped s, C(4)^A and C(4)*), 62.36, 62.45*, and 62.55 (three s, $NOCH_3^A$, $NOCH_3^B$, and $NOCH_3$*), 63.96, 64.07*, and 64.18 (three s, C(1)^A, C(1)^B, and C(1)*), 126.8 (two overlapping s, *p*-PPh), 127.1 and 127.2 (two s, *m*-PPh), 133.5* (d, $^2J_{CP}$ = 11, *o*-PPh*), 133.9 (d, $^2J_{CP}$ = 11, *o*-PPh), 140.6 (d, $^1J_{CP}$ = 21, C(1) of PPh), 190.3*, 190.6, and 190.8 (three s, C=N^A, C=N^B, and C=N*). ^{31}P{^{1}H} NMR (δ, ppm): 33.7 and 33.8*. Anal. calcd for the mixture,

$C_{362}H_{564}Cl_{12}N_{22}O_{22}P_{12}Pd_{23}$: C, 49.29; H, 6.44; N, 3.49%. Found: C, 49.40; H, 6.42; N, 3.47%.

(*S*$_C$,*S*$_C$)-*μ*-Chloro-*μ*-(*tert*-butylphenylphosphido)bis{2-[1-(*N*,*N*-dimethylamino)ethyl]phenyl-*C*,*N*}dipalladium(II) (96f). CPC **95** (38.5 mg, 0.0664 mmol) was reacted in PhMe with HP*t*-BuPh (11.0 mg, 0.0664 mmol) for 18 h at 40 °C followed by purification using preparative TLC (125:125:1 CH_2Cl_2–hexane–acetone). Compound **96f** was obtained in the amount of 29.8 mg (72% yield) as a light yellow solid. R_f = 0.38 (1:1 CH_2Cl_2–hexane); m.p. 166–168 °C (dec.); $[\alpha]_D^{20}$ = +178° (*c* 0.0044, acetone). ^{1}H NMR (δ, ppm): 1.48 (d, 3H, ^3J = 6, CHC$\underline{H}_3^A$), 1.59 (d, 9H, $^3J_{HP}$ = 15, C(CH_3)$_3$), 1.72 (d, 3H, ^3J = 6, CHC$\underline{H}_3^B$), 2.38, 2.51, 2.58, and 2.70 (four s, 12H, NCH_3), 3.35–3.42 (m, 1H, C$\underline{H}^B$CH_3), 3.95–4.01 (m, 1H, C$\underline{H}^A$CH_3), 6.04 and 6.29 (two dd, 2H, $^4J_{HP}$ = 4, ^3J = 8, H(6)^A and H(6)^B), 6.43–6.52 (m, 2H, H(5)A and H(5)^B), 6.74–6.81 (m, 3H, H(4)^A, H(4)^B, and H(3)^A), 6.87 (d, 1H, ^3J = 7, H(3)^B), 7.26–7.33 (m, 3H, *m*- and *p*-PPh), 8.11 (t, 2H, ^3J = $^3J_{HP}$ = 8, *o*-PPh). ^{13}C{^{1}H} NMR (δ, ppm): 16.4 and 24.1 (2 CH$\underline{C}$H$_3$), 32.9 (d, $^2J_{CP}$ = 7, C($\underline{C}$H$_3$)$_3$), 34.6 (d, $^1J_{CP}$ = 14, P$\underline{C}$(CH$_3$)$_3$), 42.9, 45.4, 48.3, and 50.5 (4 NCH$_3$), 71.5 and 73.9 (two d, $^3J_{CP}$ = 2, 2 $\underline{C}$HCH$_3$), 122.5 and 122.7 (two s, 2 C(3) arom), 123.4 and 123.6 (two s, 2 C(4) arom), 124.5 and 124.9 (two d, $^3J_{CP}$ = 4.4, 2 C(5) arom), 127.9 (br s, *m*-PPh), 128.1 (d, $^4J_{CP}$ = 3, *p*-PPh), 135.1 (br s, *o*-PPh), 136.2 and 137.3 (two d, $^3J_{CP}$ = 8, 2 C(6) arom), 138.9 (d, $^1J_{CP}$ = 14, C(1) of PPh), 144.9 and 148.1 (two d, $^2J_{CP}$ = 4, 2 PdC(1) arom), 153.23 and 155.2 (two d, $^3J_{CP}$ = 2, 2 C(2) arom). ^{31}P{^{1}H} NMR (δ, ppm): 45.7. Anal. calcd for $C_{38}H_{54}ClN_2PPd_2$: C, 50.75; H, 5.96; N, 3.95%. Found: C, 50.51; H, 5.95; N, 3.84%.

(*S*,*S*)-Di-*μ*-chlorobis{2-[2-(4-*tert*-butyl)oxazolinyl]-2-methyl]propyl-*C*,*N*}dipalladium(II) (97). $Pd(OAc)_2$ (69.1 mg, 0.308 mmol) and 1.8 mL of acetic acid

were added to a flask with a stir bar. (*S*)-2,4-Di-*tert*-butyl-2-oxazoline (56.4 mg, 0.308 mmol) was added by syringe dropwise while stirring. The reaction mixture was heated to 96 °C (oil bath) upon stirring for 1 h. The acetic acid was then removed under reduced pressure at rt. Acetone (2 mL) was added along with LiCl (52.0 mg, 1.23 mmol) and the solution was stirred overnight at rt. The solution was diluted with hexane (4 mL) and then filtered. The solvent was removed under reduced pressure at rt. Preparative TLC was performed using 1:4 ethyl acetate-hexane. Compound **97** was obtained in the amount of 60.0 mg (30% yield) as a yellow solid. R_f = 0.40 (1:1 CH_2Cl_2–hexane); m.p. 143–145 °C; $[\alpha]_D^{20}$ = +535° (*c* 1.21, acetone). ^{1}H NMR (δ, ppm): 0.99 (d, 9H, $C(CH_3)_3$), 1.05 and 1.40 (two s, 6H, two CH_3), 1.87 and 2.14 (two d, 2H, ^2J = 8, $PdCH_2$), 3.63 (br s, 1H, ^3J = 9, NCH), 4.21 (t, 1H, ^2J = ^3J = 9, OCH_2^A), 4.41 (dd, 1H, ^3J = 4, ^2J = 9, OCH_2^B). ^{13}C{^{1}H} NMR (δ, ppm): 26.1 ($C(\underline{C}H_3)_3$), 26.5 and 28.2 (two CH_3), 28.3 ($PdCH_2$), 34.7 ($\underline{C}(CH_3)_3$), 41.5 ($\underline{C}C$=N), 70.8 (NCH), 71.2 (OCH_2), 182.9 (C=N). Anal. calcd for $C_{22}H_{40}Cl_2N_2O_2Pd_2$: C, 40.76; H, 6.22; N, 4.32%. Found: C, 41.24; H, 6.53; N, 4.16%.

(*S,S*)-*μ*-Chloro-*μ*-(*tert*-butylphenylphosphino)bis{2-[2-(4-*tert*-butyl)oxazolinyl]-2-methyl]propyl-*C,N*}dipalladium(II) (98f). CPC **97** (19.5 mg, 0.0301 mmol) was reacted in CH_2Cl_2 with HP*t*-BuPh (45.0 mg, 0.2708 mmol) for 96 h at 35 °C followed by purification with preparative TLC (125:125:1 CH_2Cl_2–hexane–acetone). Compound **98f** was obtained in the amount of 15.6 mg (67% yield) as a light yellow solid. R_f 0.45 (1:1 CH_2Cl_2–hexane); m.p. 195–196 °C (dec.); $[\alpha]_D^{20}$ = +696° (*c* 0.460, acetone). ^{1}H NMR (δ, ppm, the prime sign was used to differentiate the data for two non-equivalent cyclopalladated ligands): 0.66 (dd, 1H, $^2J_{HP}$ = 6, ^2J = 9, $PdCH^A$), 0.95 (s, 9H, $C(CH_3)_3$), 0.96–0.99 (m, 7H, 2 CH_3 and $PdCH^{A'}$), 1.01 (s, 9H, $C(CH_3)_3$), 1.05 (s, 3H, CH_3), 1.30 (s,

3H, CH_3), 1.35 (dd, $^2J_{HP}$ = 6, ^2J = 10, $PdCH^B$), 1.58 (d, 1H, ^2J = 9, $PdCH^{B'}$), 1.65 (d, 9H, $^3J_{HP}$ = 14, $PC(CH_3)_3$), 3.79 (two overlapping dd, 2H, ^3J = 4, ^3J = 9, 2 NCH), 4.17 and 4.23 (two t, 2H, ^2J = ^3J = 9, OCH^A and $OCH^{A'}$), 4.38 (two overlapping dd, 2H, ^3J = 4, ^2J = 9, OCH^B and $OCH^{B'}$), 7.15 (t, 1H, ^3J = 7, *p*-PPh), 7.21–7.27 (m, 2H, *m*-PPh), 7.90 (dd, ^3J = 8, $^3J_{HP}$ = 10, *o*-PPh). $^{13}C\{^1H\}$ NMR (δ, ppm): 26.2 and 26.3 (two s, 2 $C(CH_3)_3$), 26.9 (d, $^2J_{CP}$ = 2, $PdCH_2$), 28.1, 28.5, 28.9, and 29.9 (4 CH_3), 31.1 (d, $^2J_{CP}$ = 3, $PdCH_2'$), 32.2 (d, $^2J_{CP}$ = 7, $PC(\underline{C}H_3)_3$), 33.9 (d, $^1J_{CP}$ = 16, $P\underline{C}(CH_3)_3$), 34.6 (two s, 2 $\underline{C}(CH_3)_3$), 42.0 and 42.2 (2 $\underline{C}C$=N), 69.9 and 70.1 (2 NCH), 71.7 (OCH_2), 71.8 (d, $^4J_{CP}$ = 2, OCH_2'), 126.5 (d, $^4J_{CP}$ = 2, *p*-PPh), 127.2 (d, $^3J_{CP}$ = 10, *m*-PPh), 133.8 (d, $^2J_{CP}$ = 12, *o*-PPh), 140.7 (d, $^1J_{CP}$ = 19, C(1) of PPh), 182.2 and 182.3 (2 C=N). $^{31}P\{^1H\}$ NMR (δ, ppm): 32.5. Anal. calcd for $C_{32}H_{54}ClN_2O_2PPd_2$: C, 49.40; H, 7.00; N, 3.60%. Found: C, 49.87; H, 7.28; N, 3.73%.

III.2.3. Sample Preparation and Procedures for ^{31}P NMR Monitoring

CPC **77** and 9 equivalents of Cs_2CO_3 were placed in a J. Young NMR tube at rt. The tube was vacuumed and filled with Ar 5 times. Under an Ar atmosphere, degassed toluene-d_8 was added. The concentration of CPC solutions was ca. 5 mg/mL. Then the NMR tube was frozen by placing it in liquid nitrogen. The specified amount of $HPPh_2$ was added and $^{31}P\{^1H\}$ NMR spectra were recorded at rt.

III.3. Preparation of Products from CPCs and m*-Chloroperoxybenzoic Acid*

III.3.1. General Oxidation Procedure

A solution of the starting CPC (25 mg/mL) and a stir bar were added to a small round-bottom flask. A solution of 2.7 equivalents of *m*-CPBA (unless otherwise specified) in solvent (MeCN, EtOAc or CH_2Cl_2, 40 mg/mL) was added dropwise to the CPC solution while stirring. The flask was stoppered, and the mixture was allowed to stir for 18 h (unless

otherwise specified) at rt. The crude solution was washed several times with saturated $NaHCO_3$ aqueous solution and then with water. The combined aqueous layers were extracted with either EtOAc or CH_2Cl_2. The combined organic layers were dried over magnesium or sodium sulfate, filtered, and the solvent was evaporated on a rotavapor. The crude mixture, unless otherwise indicated, was dissolved in 5 mL of acetone and stirred for 45 min at rt with 10 equivalents of LiCl. The solvent was removed and the mixture dissolved in CH_2Cl_2 then filtered through 1 cm of celite. Products were isolated using either preparative TLC or column chromatography.

III.3.2. Compounds Synthesized from Oxidation of CPCs with m-*CPBA*

(*S*,*S*)-Di-μ-chlorobis{2-[2-(4-*tert*-butyl)oxazolinyl]phenolato-κ^2-*N*,*O*}dipalladium(II) (100a). The compound was obtained according to the general oxidation procedure described above using complex **105a** (32.5 mg, 0.0442 mmol), *m*-CPBA (20.6 mg, 0.119 mmol) and EtOAc (2.5 mL); the reaction mixture was stirred at rt for 18 h. Preparative TLC was performed using 1:1:18 EtOAc–CH_2Cl_2–hexane. Five fractions were collected of which the bottom one was recrystallized from toluene giving 4.8 mg of brown solid (15%). R_f = 0.41 (1:4 EtOAc–hexanes); m.p. 120–123 °C (dec.); $[\alpha]^{22}_D$ = + 0.110 (*c* 0.400, acetone). ^{1}H NMR (δ, ppm): 1.17 (s, 9H, $(CH_3)_3C$), 3.85 (dd, 1H, *J* = 2.2, 9.0, OCH_2), 4.44 (t, 1H, *J* = 9.0, NCH), 4.55 (dd, 1H, *J* = 2.2, 9.0, OCH), 6.59 (ddd, 1H, arom. CH), 6.90 (d, 1H, *J* = 8.3, arom. CH), 7.19 (ddd, 1H, *J* = 1.8, 6.8, 8.3, arom. CH), 7.49 (dd, 1H, *J* = 1.8, 8.3). ^{13}C{^{1}H} NMR (δ, ppm): 26.5 (($\underline{C}H_3)_3C$), 35.4 (($CH_3)_3\underline{C}$), 70.8 (NCH), 71.3 (OCH_2), 110.2 (arom. CH), 116.5 (arom. C), 120.3 (arom. CH), 129.7 (arom. CH), 135.1 (arom. CH), 162.8 (arom. CO), 167.5 (C=N). Anal. calcd for $C_{26}H_{32}Cl_2N_2O_4Pd_2 \cdot 0.5$ PhMe: C, 46.23; H, 3.66; N, 4.74. Found: C, 46.64; H, 4.10; N, 4.56%.

(*S*,*S*)-Di-μ-chlorobis{2-[2-(4-ethyl)oxazolinyl]phenolato-κ^2-*N*,*O*}dipalladium(II) (100b). The compound was obtained according to the general oxidation procedure described above using complex **99b** (87.7 mg, 0.139 mmol), *m*-CPBA (143.4 mg, 0.8310 mmol) and CH_2Cl_2 (6 mL). Two consecutive preparative TLC purifications were performed, first using 1:4 CH_2Cl_2−petroleum ether as the eluent, then 1:1 CH_2Cl_2−petroleum ether. Five fractions were collected, of which the bottom two contained the product. These fractions were combined and washed with ether and hexanes, then recrystallized from toluene to give 10 mg of a brown solid (9%). R_f = 0.26 (1:4 EtOAc−hexanes); m.p. 140−142 °C; $[\alpha]^{22}_D$ = −0.0750 (*c* 0.375, acetone). ^{1}H NMR (δ, ppm): 1.02 (s, 3H, *J* = 7.5, CH_3), 1.82−1.93 (m, 1H, $\underline{CH_2}CH_3$), 2.28−2.39 (m, 1H, $\underline{CH_2}CH_3$), 4.26 (t, 1H, *J* = 8.8, OCH_2), 4.29−4.38 (m, 1H, NCH), 4.65 (t, 1H, *J* = 8.8, OCH_2), 7.36−7.43 (m, 1H, arom. CH), 7.44−7.54 (m, 2H, arom. CH), 8.32 (d, 1H, *J* = 7.3 Hz, arom. CH). ^{13}C{^{1}H} NMR (δ, ppm): 9.3 (CH_3), 27.5 ($\underline{C}H_2CH_3$), 67.0 (NCH), 73.3 (OCH_2), 126.3 (arom. CH), 127.2 (arom. C), 130.2 (arom. CH), 132.5 (arom. CH), 132.6 (arom. CH), 133.9 (arom. CO), 167.1 (C=N). Anal. calcd for $C_{22}H_{24}Cl_2N_2O_4Pd_2$·0.5 PhMe: C, 43.12; H, 3.97; N, 3.94%. Found: C, 43.06; H, 3.60; N, 3.79%.

(*S*,*S*)-Di-μ-(3-chlorobenzoato)bis{2-[2-(4-*tert*-butyl)oxazolinyl]phenolato-κ^2-*N*,*O*}dipalladium(II) (101a). The compound was obtained according to the general oxidation procedure described above using complex **99a (**76.4 mg, 0.111 mmol), *m*-CPBA (53.6 mg, 0.300 mmol) and EtOAc (6 mL). Instead of acetone and LiCl, the crude residue was dissolved in PhMe (5 mL), the flask was covered in aluminum foil, and silver *m*-chlorobenzoate was added (146 mg, 0.554 mmol). After stirring for 45 min at rt, the mixture was filtered through 1 cm of celite. Purification using preparative TLC (1:1:18

EtOAc−CH_2Cl_2−hexanes) afforded 23.0 mg of compound **101a** as a red-orange solid (22%). R_f = 0.51 (1:4 EtOAc−hexanes); m.p. 148–151 (dec.); $[\alpha]_D^{23}$ = +256° (*c* 0.117, acetone). IR (ν, cm^{-1}, mineral oil mull): 1620 (C=N), 1560 and 1395 (COO). ^1H NMR (δ, ppm): 1.25 (s, 9H, $(CH_3)_3C$), 3.51 (dd, 1H, *J* = 8.9, 2.1, NCH), 3.59 (t, 1H, *J* = 8.9, OCH_2), 4.21 (dd, 1H, *J* = 8.9, 2.1, OCH_2), 6.54 (t, 1H, *J* ≈ 7.5, arom. CH(4) (para to COPd)), 6.81 (d, *J* = 8.2, 1H, arom. CH(6) (ortho to COPd)), 7.12–7.18 (m, 2H, arom. CH(3,5)), 7.27 (t, 1H, *J* = 8.0, CH(5) of 3-ClC_6H_4), 7.40 (dd, 1H, *J* = 1.8, 8.0, CH(6) of 3-ClC_6H_4), 7.85 (dt, 1H, *J* = 1.8, 8.0, CH(4) of 3-ClC_6H_4), 7.98 (7, 1H, *J* = 1.8, CH(2) of 3-ClC_6H_4). $^{13}C\{^1H\}$ NMR NMR (δ, ppm): 25.9 ($(\underline{C}H_3)_3C$), 35.1 $(CH_3)_3\underline{C}$), 69.8 (NCH), 70.1 (OCH_2), 109.7 (arom. C(2)), 115.3 (arom. CH(4) (para to C(1)OPd)), 119.4 (arom. CH(6) (ortho to COPd)), 128.0 (CH(4) of 3-ClC_6H_4), 129.2 (CH(5) of 3-ClC_6H_4), 130.2 (CH(2) of 3-ClC_6H_4), 130.3 (arom. CH(3)), 132.1 (CH(6) of 3-ClC_6H_4), 134.0 (arom. C(1) of 3-ClC_6H_4), 134.21 (arom. CH(5)), 134.23 (arom. ClC(3) of 3-ClC_6H_4), 162.1 (arom. OC(1)), 167.5 (C=N), 177.6 ($Ar\underline{C}O_2$). Anal. calcd for $C_{40}H_{40}Cl_2N_2O_8Pd_2$: C, 50.02; H, 4.20; N, 2.92%. Found: C, 50.13; H, 4.26; N, 3.00%.

(*S*,*S*)-Di-μ-(3-chlorobenzoato)bis{2-[2-(4-ethyl)oxazolinyl]phenolato-κ^2-*N*,*O*}dipalladium(II) (101b). The compound was obtained according to the general oxidation procedure described above using complex **99b** (65.0 mg, 0.102 mmol), *m*-CPBA (84.0 mg, 0.487 mmol) and EtOAc (5 mL). Instead of acetone and LiCl, the crude residue was dissolved in PhMe (5 mL), the flask was covered in aluminum foil, and silver *m*-chlorobenzoate was added (134 mg, 0.510 mmol). After stirring for 45 min at rt, the mixture was filtered through 1 cm of celite. Preparative TLC (1:1:18 EtOAc−CH_2Cl_2−hexanes) afforded 18.0 mg (19%) of complex **101b** as an orange solid. R_f

= 0.39 (1:4 EtOAc−hexanes); m.p. 126–128 °C; $[\alpha]^{23}_D$ = –193 (*c* 0.155 acetone). ^{1}H NMR (*δ*, ppm): 0.94 (s, 9H, CH_3), 1.80–1.90 (m, 1H, C$\underline{H}_2$CH$_3$), 2.08–2.19 (m, 1H, C$\underline{H}_2$CH$_3$), 3.72–3.79 (m, 1H, NCH), 3.85 (t, 1H, *J* = 8.2, OCH_2), 4.01 (dd, 1H, *J* = 4.7, 8.2, OCH_2), 6.52 (dt, 1H, *J* = 1.0, 7.8, CH(4) (para to COPd)), 6.82 (d, 1H, *J* ≈ 9, CH(6) (ortho to arom. COPd)), 7.08–7.16 (m, 2H, arom. CH(3,5)), 7.27 (t, 1H, *J* ≈ 8, CH(5) of 3-ClC_6H_4), 7.39–7.43 (ddd, 1H, *J* ≈ 1, 2, 8, CH(6) of 3-ClC_6H_4), 7.85 (dt, 1H, *J* ≈ 1, 8, CH(4) of 3-ClC_6H_4), 7.98 (t, 1H, *J* ≈ 2, CH(2) of 3-ClC_6H_4). ^{13}C{^{1}H} NMR (*δ*, ppm): 8.8 (CH_3), 28.0 ($\underline{C}H_2CH_3$), 63.9 (NCH), 72.4 (OCH_2), 109.5 (arom. C(2)), 115.4 (arom. CH(4) (para to C(1)OPd)), 119.3 (arom. CH(6) (ortho to COPd)), 128.0 (arom. CH(4) of 3-ClC_6H_4), 129.2 (arom. CH(5) of 3-ClC_6H_4), 129.8 (arom. CH(3)), 130.2 (CH(2) of 3-ClC_6H_4), 132.2 (CH(6) of 3-ClC_6H_4), 133.8 (CH(5)), 133.9 (arom. C(1) of 3-ClC_6H_4), 134.1 (arom. ClC(3) of 3-ClC_6H_4), 160.9 (arom. OC(1)), 167.0 (C=N), 177.4 (Ar$\underline{C}O_2$). Anal. calcd for $C_{36}H_{32}N_2O_8Pd_2Cl_2$: C, 47.81; H, 3.57; N, 3.10%. Found: C, 47.74; H, 3.67; N, 3.09%.

(*S,S*)-Bis{2-[2-(4-*tert*-butyl)oxazolinyl]phenolato-κ^2-*N,O*}palladium(II) (102a). The compound was obtained according to the general oxidation procedure described above using complex **99a** (26.9 mg, 0.0391 mmol), *m*-CPBA (18.2 mg, 0.105 mmol) and MeCN (2 mL). Preparative TLC (1:1:18 EtOAc−CH_2Cl_2−hexanes) afforded 4.2 mg (20%) of complex **102a** as a yellow solid. R_f = 0.63 (1:20 hexanes−CH_2Cl_2); m.p. 220 °C (dec.) (lit. data: 278−279 ºC [58]); $[\alpha]_D^{22}$ = +770° (lit. data +800º in thf,[187] *c* 0.020, *tert*-butyl methyl ether). IR (*ν*, cm^{-1}, mineral oil mull): 1612 (C=N). The ^{1}H NMR spectrum was identical to already published data.[187] ^{13}C{^{1}H} NMR (*δ*, ppm): 25.0 (($\underline{C}H_3$)$_3$C), 33.8 ((CH$_3$)$_3\underline{C}$), 65.0 (NCH), 69.2 (OCH_2), 108.7 (arom. C(1)), 113.1 (arom. CH), 120.1 (arom. CH), 128.5 (arom. CH), 132.8 (arom. CH), 162.3 (arom. OC(2)), 167.5 (C=N).

(*S,S*)-Bis{2-[2-(4-ethyl)oxazolinyl]phenolato-κ^2-*N,O*}palladium(II) (102b). The compound was obtained according to the general oxidation procedure described above using complex **99b** (24.6 mg, 0.0389 mmol), *m*-CPBA (18.2 mg, 0.105 mmol) and MeCN (2 mL). Purification using preparative TLC (1:2:7 EtOAc−CH_2Cl_2−hexanes) afforded 2.9 mg (11%) of the product as a yellow solid. [The same reaction also provided **100b** (9%) and **103b** (11%).] R_f 0.37 (1:1:18 EtOAc−CH_2Cl_2−hexanes); m.p. 144–147 °C; $[\alpha]_D^{23}$ = −49.3 (*c* 0.125, acetone). IR (*v*, cm^{-1}, mineral oil mull): 1622 (C=N). The ^1H NMR spectrum was identical to already published data.[189] ^{13}C {^1H} NMR (δ, ppm): 9.5 (Me), 28.2 ($\underline{C}H_2Me$), 62.6 (NCH), 72.4 (OCH_2), 109.5 (arom. C(1)), 114.6 (arom. CH), 121.3 (arom. CH), 129.4 (arom. CH), 133.7 (arom. CH), 162.0 (arom. OC(2)), 167.9 (C=N).

(*S,S*)-Di-μ-chloro{2-[2-(4-*tert*-butyl)oxazolinyl]phenolato-κ^2-*N,O*}{2-[2-(4-*tert*-butyl)oxazolinyl]phenyl-κ^2-*C,N*}dipalladium(II) (103a). The compound was obtained according to the general procedure described above using complex **99a** (30.3 mg, 0.0440 mmol), *m*-CPBA (20.5 mg, 0.119 mmol) and EtOAc (2.5 mL). Purification using preparative TLC (1:1:18 EtOAc–CH_2Cl_2–hexane) followed by recrystallization from toluene afforded 4.1 mg (13%) of complex **103a** as an orange solid. [The same reaction also provided **102a** (13%).] R_f = 0.58 (1:2:7 EtOAc−CH_2Cl_2−hexane); m.p. = 92−93 °C; $[\alpha]^{23}_D$ = +292 (*c* 0.110, acetone); IR (*v*, cm^{-1}, mineral oil mull): 1616 (C=N). ^1H NMR (δ, ppm; signals assigned to the oxygenated 2-phenyl-oxazoline moiety are marked with an asterisk): 0.95* (s, 9H, $(CH_3)_3C$), 1.35 (s, 9H, $(CH_3)_3C$), 4.22 (dd, 1H, *J* = 7.2, 10.8, OCH_2), 4.29-4.37* (m, 2H, NCH), 4.41* (d, 1H, *J* = 7.2, OCH_2), 4.52-4.63 (m, 2H, NCH), 6.47* (ddd, 1H, *J* = 1.0, 7.0, 8.5, (CH(4) (para to COPd), 6.71* (d, 1H, *J* = 8.9, arom. CH(6) (ortho to COPd)), 7.14* (ddd, 1H, *J* = 1.9, 7.0, 8.5, arom. CH(5)), 7.40-7.50 (m, 4H, arom.

CH), 8.42 (d, 1H, J = 7.2, arom. CH). $^{13}C\{^{1}H\}$ NMR (δ, ppm): 26.4* (($\underline{C}H_3)_3C$), 26.7 (($\underline{C}H_3)_3C$), 34.5* (($CH_3)_3\underline{C}$), 35.2 (($CH_3)_3\underline{C}$), 70.0* (NCH), 70.3* (OCH_2), 71.5 (NCH), 74.4 (OCH_2), 110.0* (arom. C(2)), 114.8* (CH(4) (para to COPd)), 121.0* (arom. CH(6) (ortho to COPd)), 126.7 (arom. CH), 128.2 (arom. C(2)), 129.8* (arom. CH(3)), 130.1 (arom. CH), 132.6 (arom. CH), 132.9 (arom. CH), 133.6 (arom. PdC(1)), 134.4* (arom. CH(5)), 162.8* (arom. OC(1)), 167.9* (C=N), 168.8 (C=N). Anal. calcd for $C_{26}H_{32}Cl_2N_2O_3Pd_2 \cdot 1.5$ PhMe: C, 52.04; H, 5.26%. Found: C, 52.48; H, 5.35%.

(*S*,*S*)-Di-μ-chloro{2-[2-(4-ethyl)oxazolinyl]phenolato-κ^2-*N*,*O*}{2-[2-(4-ethyl)oxazolinyl]phenyl-κ^2-*C*,*N*}dipalladium(II) (103b). The compound was obtained according to the general oxidation procedure described above using complex **99b** (100.7 mg, 0.1593 mmol), *m*-CPBA (74.2 mg, 0.430 mmol) and EtOAc (7.5 mL). Purification using preparative TLC (1:2:7 EtOAc−CH_2Cl_2−hexanes) followed by recrystallization from toluene afforded 31.0 mg (30%) of the product as a yellow solid. [The same reaction also provided **102b** (4%).] R_f = 0.30 (1:4 EtOAc−hexanes); m.p. 70–71°C; $[\alpha]^{23}_D$ = −179 (*c* 0.135, acetone); IR (ν, cm^{-1}, mineral oil mull): 1619 (C=N). ^{1}H NMR (δ, ppm; signals assigned to the oxygenated 2-phenyl-oxazoline moiety are marked with an asterisk): 0.83* (t, 3H, J = 7.4, CH_3), 1.13 (t, 3H, J = 7.4, CH_3), 1.61–1.70* (m, 1H, $C\underline{H}_2CH_3$), 1.82–1.90* (m, 1H, $C\underline{H}_2CH_3$), 2.19–2.28 (m, 1H, $C\underline{H}_2CH_3$), 2.28–2.38 (m, 1H, $C\underline{H}_2CH_3$), 4.28* (dd, 1H, J = 3.2, 8.6, OCH_2), 4.38* (t, 1H, J = 8.6, OCH_2), 4.42 (t, 1H, J = 8.0, OCH_2), 4.44–4.50* (m, 1H, NCH), 4.51–4.59 (m, 1H, NCH), 4.73 (dd, 1H, J = 8.4, 9.6, OCH_2), 6.48* (ddd, 1H, J = 1.2, 7.0, 8.1, arom. CH(4) (para to COPd)), 6.68* (dd, 1H, J = 1.0, 8.5, arom. CH(6) (ortho to COPd)), 7.13* (ddd, 1H, J = 1.9, 7.0, 8.5, arom. CH(5)), 7.41–7.46 (m, 3H, arom. CH), 7.44−7.48* (CH(4)), 8.46–8.51 (m, 1H, arom. CH). $^{13}C\{^{1}H\}$ NMR (δ,

ppm): 8.4* (CH_3), 8.5 (CH_3), 27.3* ($\underline{C}H_2CH_3$), 28.0 ($\underline{C}H_2CH_3$), 64.4* (NCH), 66.3 (NCH), 71.7* (OCH_2), 73.1 (OCH_2), 109.3* (arom. C(2)), 114.6* (CH(4) (para to COPd)), 120.3* (arom. CH(6) (ortho to COPd)), 126.5 (arom. CH), 127.4 (arom. C(2)), 129.3* (arom. CH(3)), 130.1 (arom. CH), 132.4 (arom. CH), 132.6 (arom. CH), 133.6 (arom. PdC(1)), 133.8*(arom. CH(5)), 161.5* (arom. OC(1)), 167.1* (C=N), 167.7 (C=N). Anal. calcd for $C_{22}H_{24}N_2O_3Pd_2Cl_2 \cdot 1$ PhMe: C, 47.05; H, 4.36%. Found: C, 46.87; H, 4.12%.

(*S,S*)-Di-μ-(3-chlorobenzoato)bis{2-[2-(4-*tert*-butyl)oxazolinyl]phenyl-κ^2-*C,N*}dipalladium(II) (106a). The compound was obtained according to the general oxidation procedure described above using complex **105a** (26.0 mg, 0.0354 mmol), *m*-CPBA (16.5 mg, 0.0956 mmol) and EtOAc (2 mL). LiCl was not used to treat the crude mixture. Purification using preparative TLC (1:4 EtOAc−hexanes) afforded 9.4 mg (29%) of complex **106a** as a yellow solid. R_f = 0.51 (4:1 hexanes−ethyl acetate); m.p. 143–146 °C; $[\alpha]_D^{22}$ = +160° (*c* 0.410, acetone); IR (ν, cm^{-1}, mineral oil mull): 1389 (COO), 1562 (COO), 1624 (C=N). ^{1}H NMR (δ, ppm): 0.88 (s, 9H, $(CH_3)_3C$), 2.75 (dd, 1H, *J* = 3.4, 9.2, OCH_2), 3.13 (t, 1H, *J* = 9.2, NCH), 4.15 (dd, 1H, *J* = 3.4, 9.2, OCH_2), 7.06−7.17 (three m, 4H, arom. CH), 7.29 (t, 1H, *J* = 8, CH(5) of 3-ClC_6H_4), 7.39 (ddd, 1H, *J* = 1, 2, 8, CH(6) of 3-ClC_6H_4), 7.99 (dd, 1H, *J* = 2, 8, CH(4) of 3-ClC_6H_4), 8.14 (t, 1H, *J* = 2, CH(2) of 3-ClC_6H_4). $^{13}C\{^1H\}$ NMR (δ, ppm): 26.1 (($\underline{C}H_3)_3C$), 35.0 (($CH_3)_3\underline{C}$), 71.0 (NCH), 71.7 (OCH_2), 124.2 (arom. CH), 126.0 (arom. CH), 128.6 (CH(4) of 3-ClC_6H_4), 129.4 (CH(5) of 3-ClC_6H_4), 130.7 (CH(2) of 3-ClC_6H_4), 130.8 (arom. CH), 131.5 (arom. C(2)), 131.5 (arom. CH), 131.7 (CH(6) of 3-ClC_6H_4), 134.2 and 136.9 (arom. C(1) and ClC(3) of 3-ClC_6H_4), 147.5 (arom. PdC(1)), 173.6 and 174.3 ($Ar\underline{C}O_2$ and C=N). Anal. calcd for $C_{40}H_{40}Cl_2N_2O_6Pd_2$: C, 51.74; H, 4.34; N, 3.02%. Found: C, 51.44; H, 4.59; N, 3.06%.

(*S*,*S*)-Di-μ-(3-chlorobenzoato)bis{2-[2-(4-ethyl)oxazolinyl]phenyl-κ^2-*C*,*N*}dipalladium(II) (106b). The compound was obtained according to the general oxidation procedure described above using complex **99b** (28.3 mg, 0.0448 mmol), *m*-CPBA (19.4 mg, 0.112 mmol) and EtOAc (2.2 mL) in a 30-min reaction. Purification by preparative TLC (1:1:18 EtOAc−CH_2Cl_2−hexanes) afforded 8.1 mg (22%) of complex **106b** as a yellow solid. R_f = 0.40 (4:1 hexanes−ethyl acetate); m.p. 195–199 °C (dec.); $[\alpha]_D^{23}$ −216° (*c* 0.199, acetone) IR (ν, cm^{-1}, mineral oil mull): 1377 (COO), 1561 (COO), 1630 (C=N). ^{1}H NMR (δ, ppm): 0.78 (t, 3H, *J* = 7.5, CH_2), 1.52 (m, 1H, C$\underline{H}_2$CH$_3$), 1.63 (m, 1H, C$\underline{H}_2$CH$_3$), 3.09 (m, 1H, NCH), 3.54 (t, 1H, *J* = 9.1, OCH_2), 3.98 (dd, 1H, *J* = 6.0, 9.1, OCH_2), 7.04–7.13 (m, 4H, arom. CH), 7.31 (t, 1H, *J* = 8.0, CH(5) of 3-ClC_6H_4), 7.40 (ddd, 1H, *J* = 1.2, 1.8, 8.0 CH(6) of 3-ClC_6H_4), 8.02 (dt, 1H, *J* = 1.2, 8.0, CH(4) of 3-ClC_6H_4), 8.15 (t, 1H, *J* = 1.8, CH(2) of 3-ClC_6H_4). ^{13}C{^{1}H} NMR (δ, ppm): 8.5 (CH_3), 26.5 ($CH_3\underline{C}H_2$), 62.2 (NCH), 74.2 (OCH_2), 123.9 (arom. CH), 125.6 (arom. CH), 128.2 (CH(4) of 3-ClC_6H_4), 129.2 (CH(5) of 3-ClC_6H_4), 130.2 (CH(2) of 3-ClC_6H_4), 130.5 (arom. CH), 131.1 (arom. C(2)), 131.3 (arom. CH), 131.4 (CH(6) of 3-ClC_6H_4), 134.0 and 136.6 (arom. C(1) and ClC(3) of 3-ClC_6H_4), 147.6 (arom. PdC(1)), 173.6 and 173.9 (Ar$\underline{C}O_2$ and C=N). Anal. calcd for $C_{36}H_{32}N_2O_6Pd_2Cl_2$: C, 49.56; H, 3.70; N, 3.21%. Found: C, 49.21; H, 3.90; N, 3.38%.

APPENDIX: Spectra and X-Ray Crystallographic Data

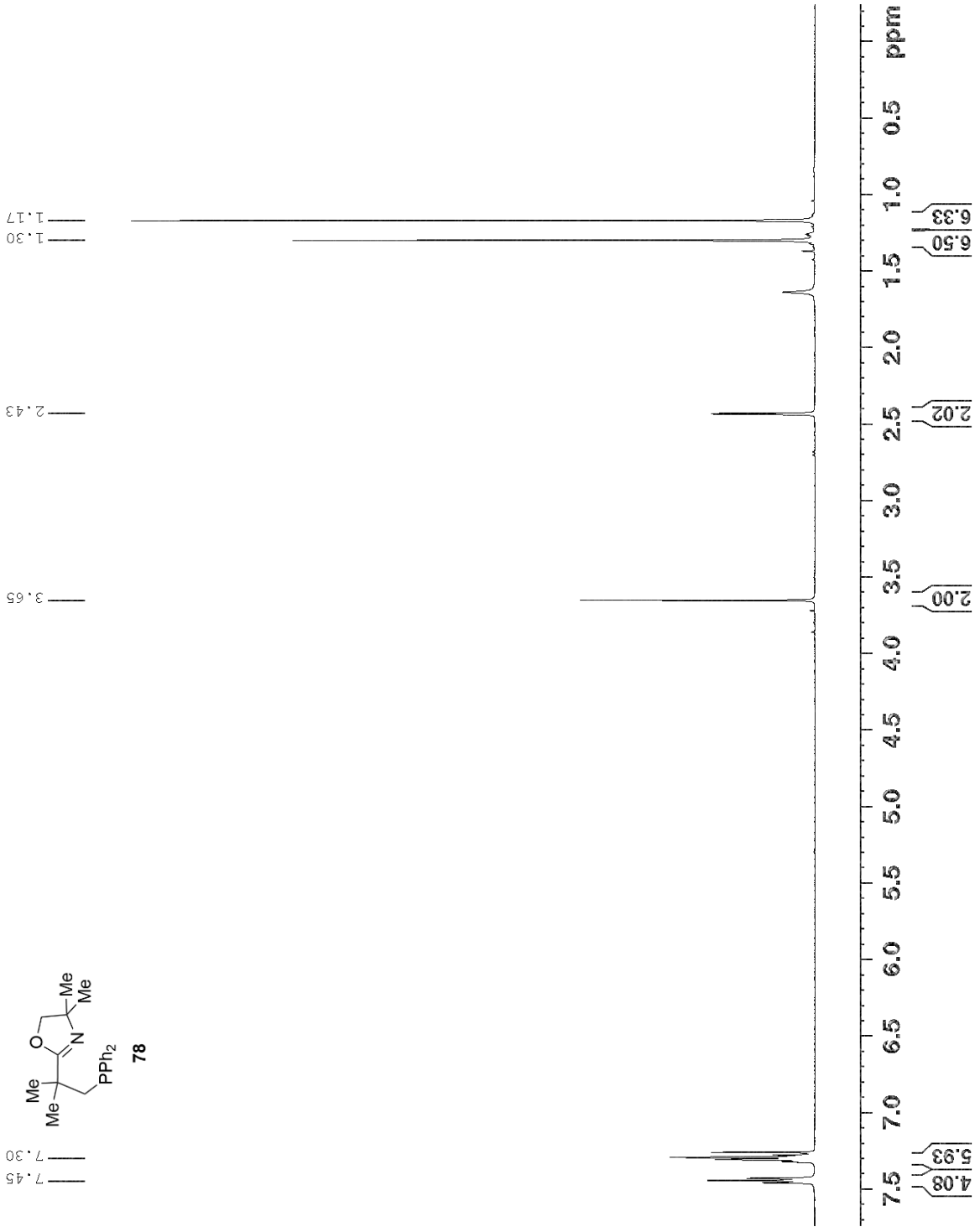


Figure 6. ^{1}H NMR spectrum of iminophosphine **78**.

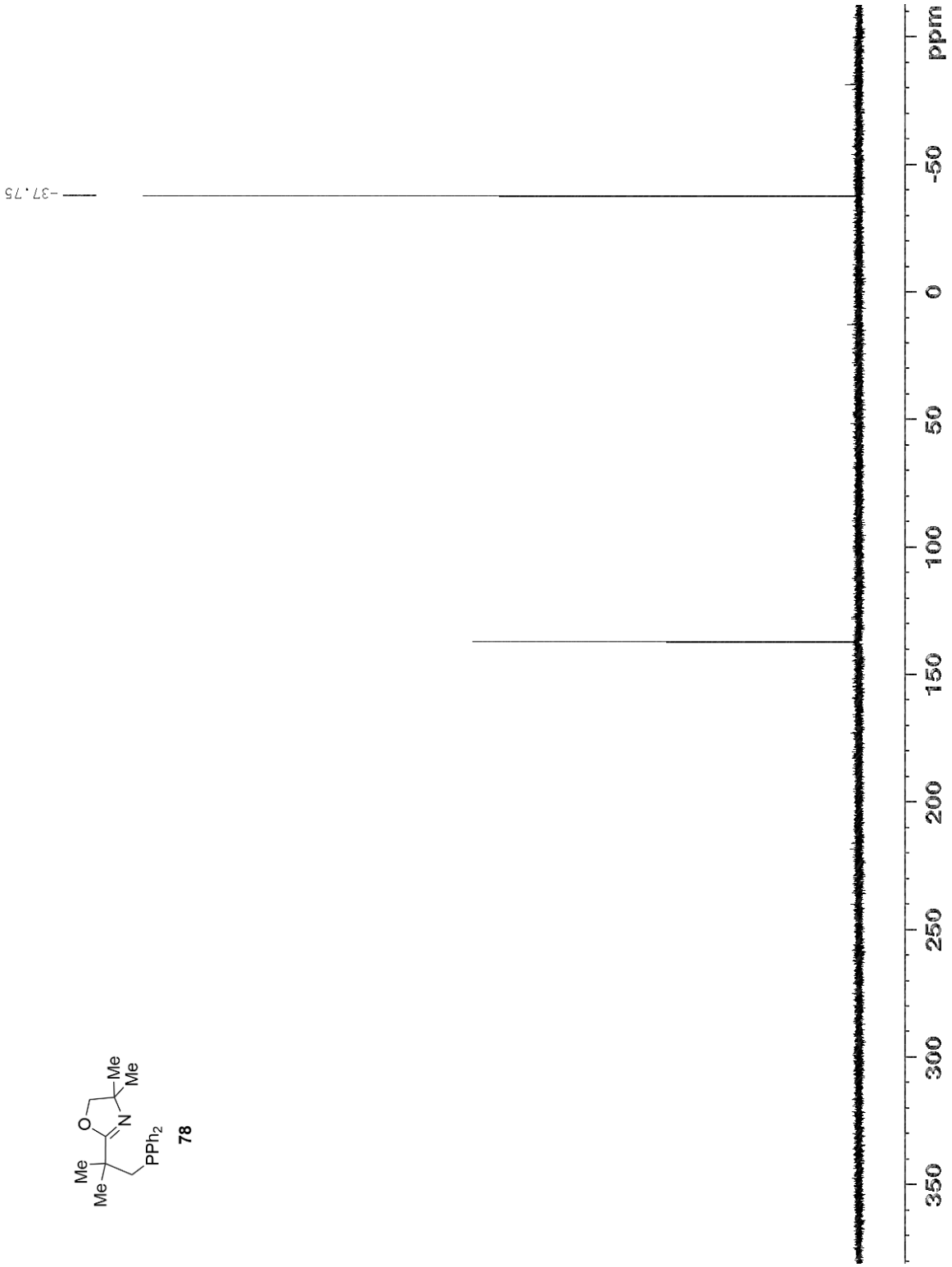


Figure 7. $^{31}P\{^{1}H\}$ NMR spectrum of iminophosphine **78**.

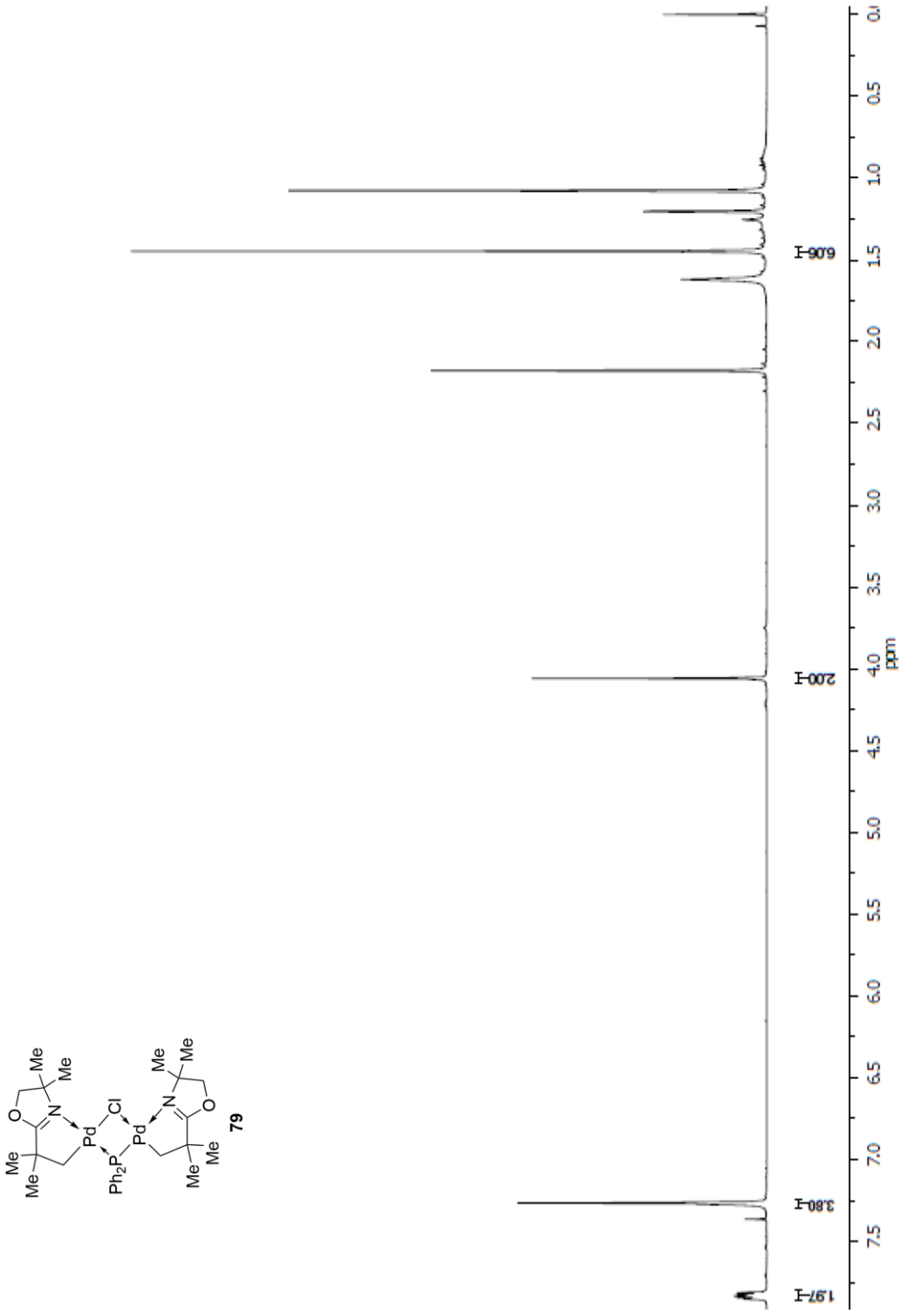


Figure 8. ^{1}H NMR spectrum of μ-chloro-μ-diphenylphosphido complex **79**.

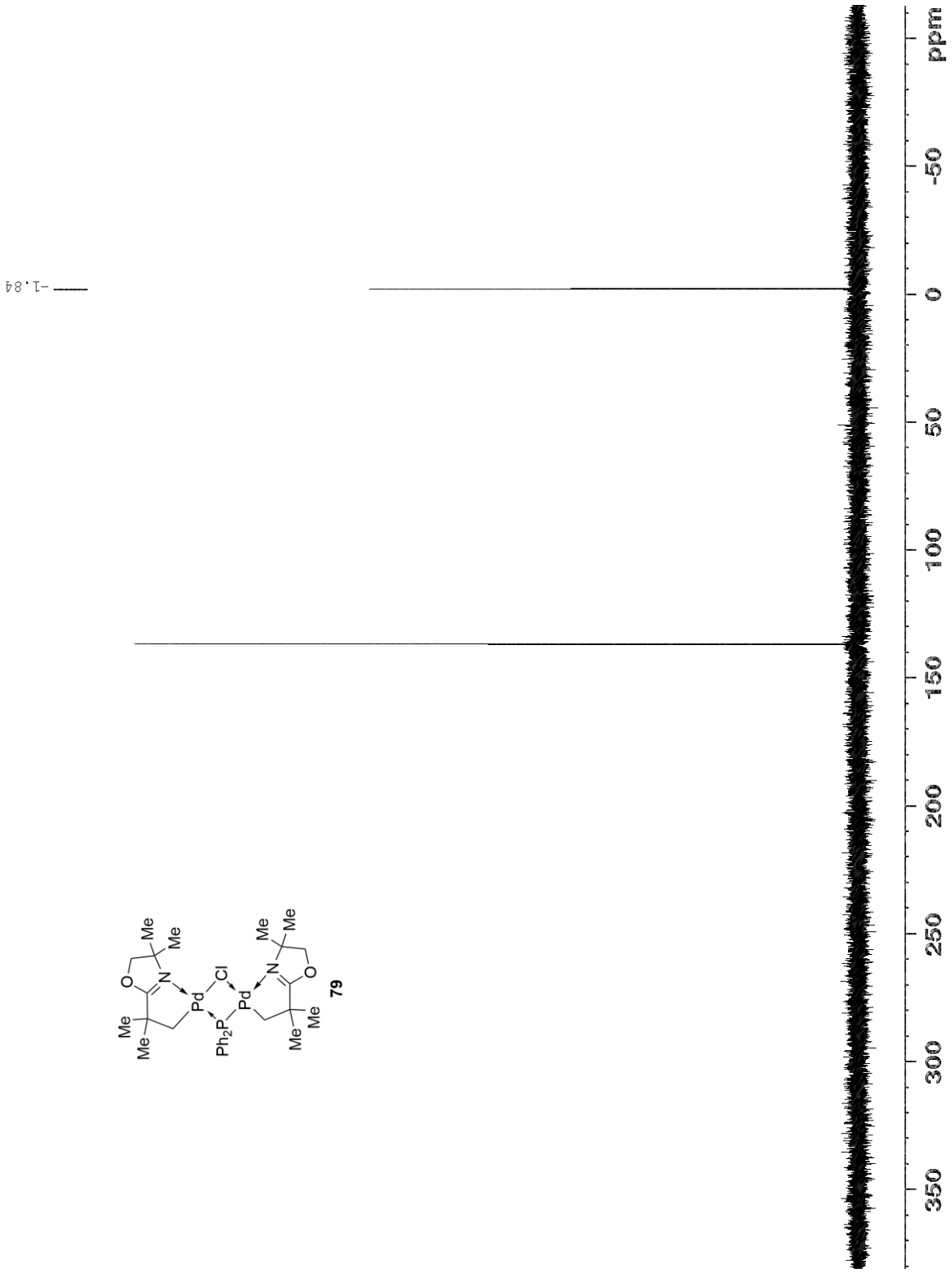


Figure 9. $^{31}P\{^{1}H\}$ NMR spectrum of μ-chloro-μ-diphenylphosphido complex **79**.

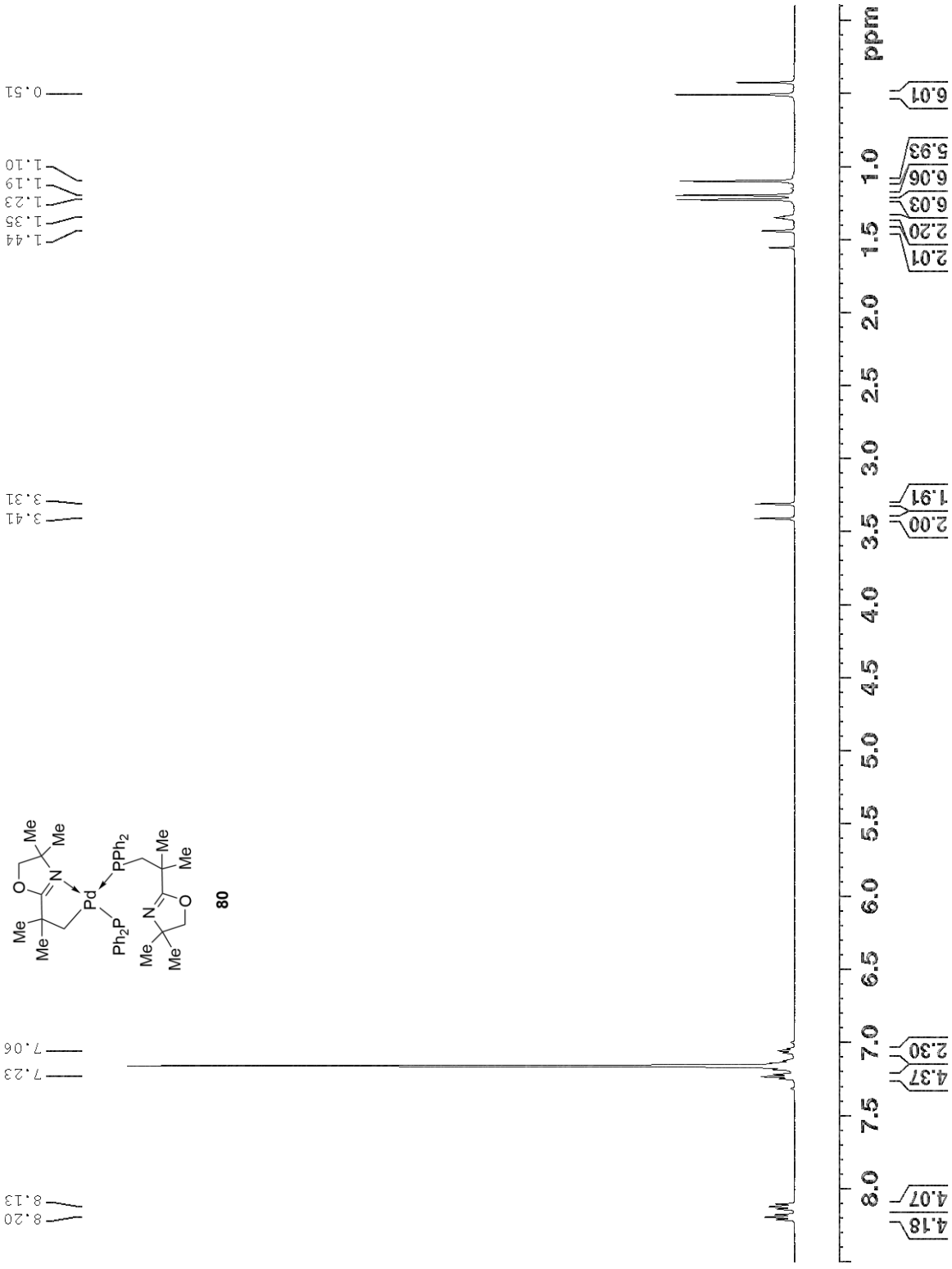


Figure 10. ^{1}H NMR spectrum of terminal phosphido complex **80** in C_6D_6.

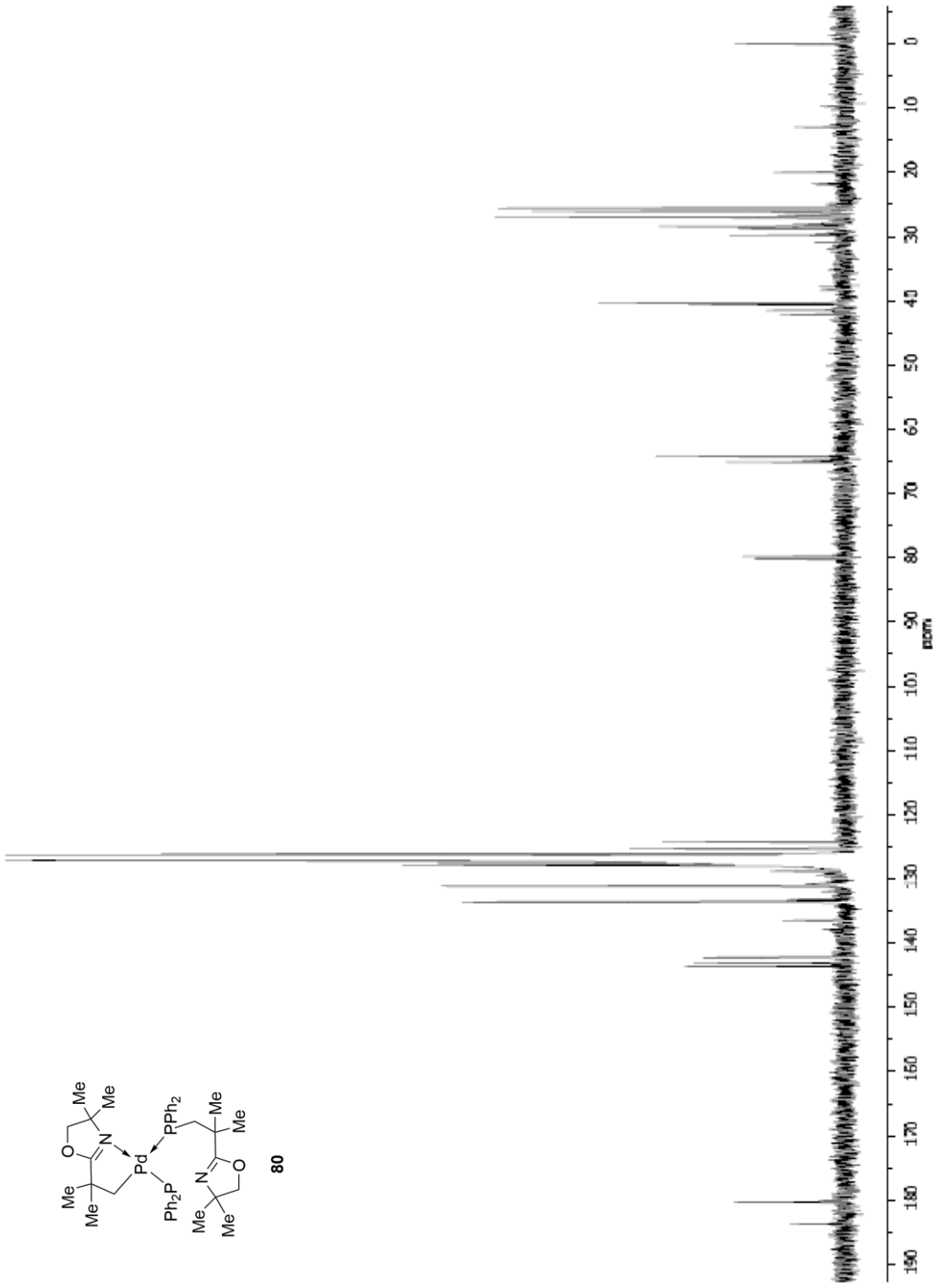


Figure 11. $^{13}C\{^{1}H\}$ NMR spectrum of terminal phosphido complex **80** in C_6D_6.

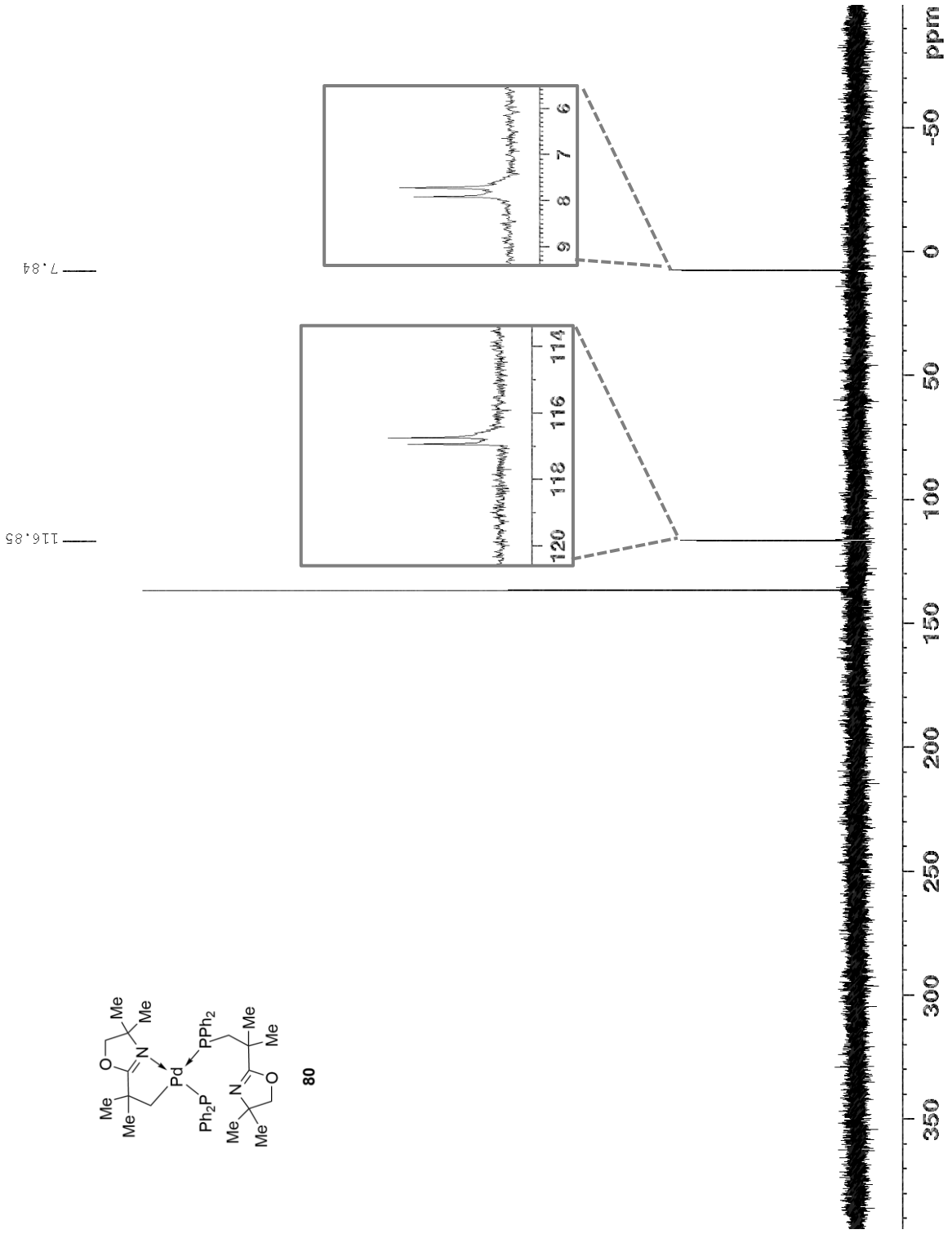


Figure 12. $^{31}P\{^{1}H\}$ NMR spectrum of terminal phosphide complex **80** in C_6D_6.

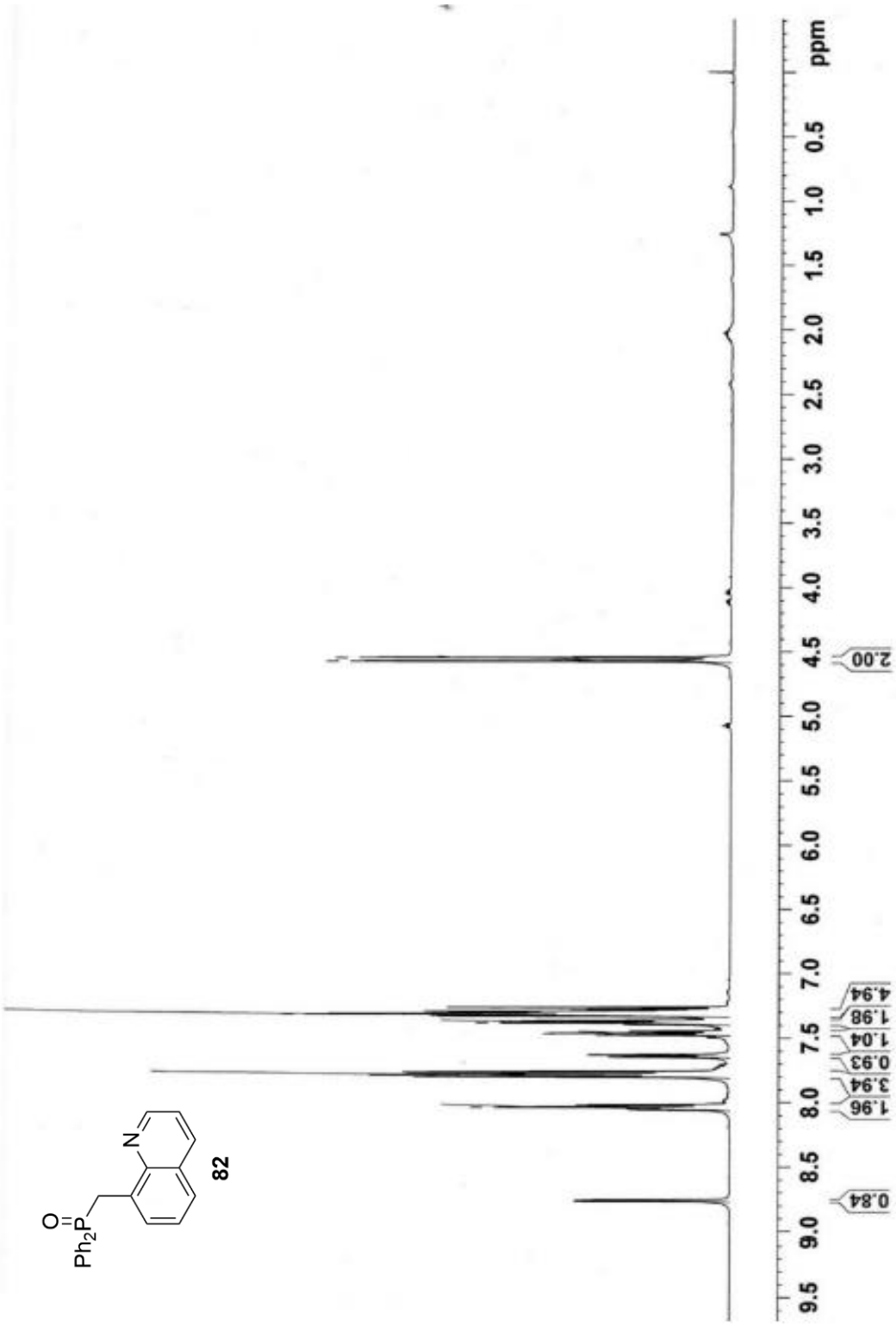


Figure 13. ^{1}H NMR spectrum of aminophosphine oxide **82**.

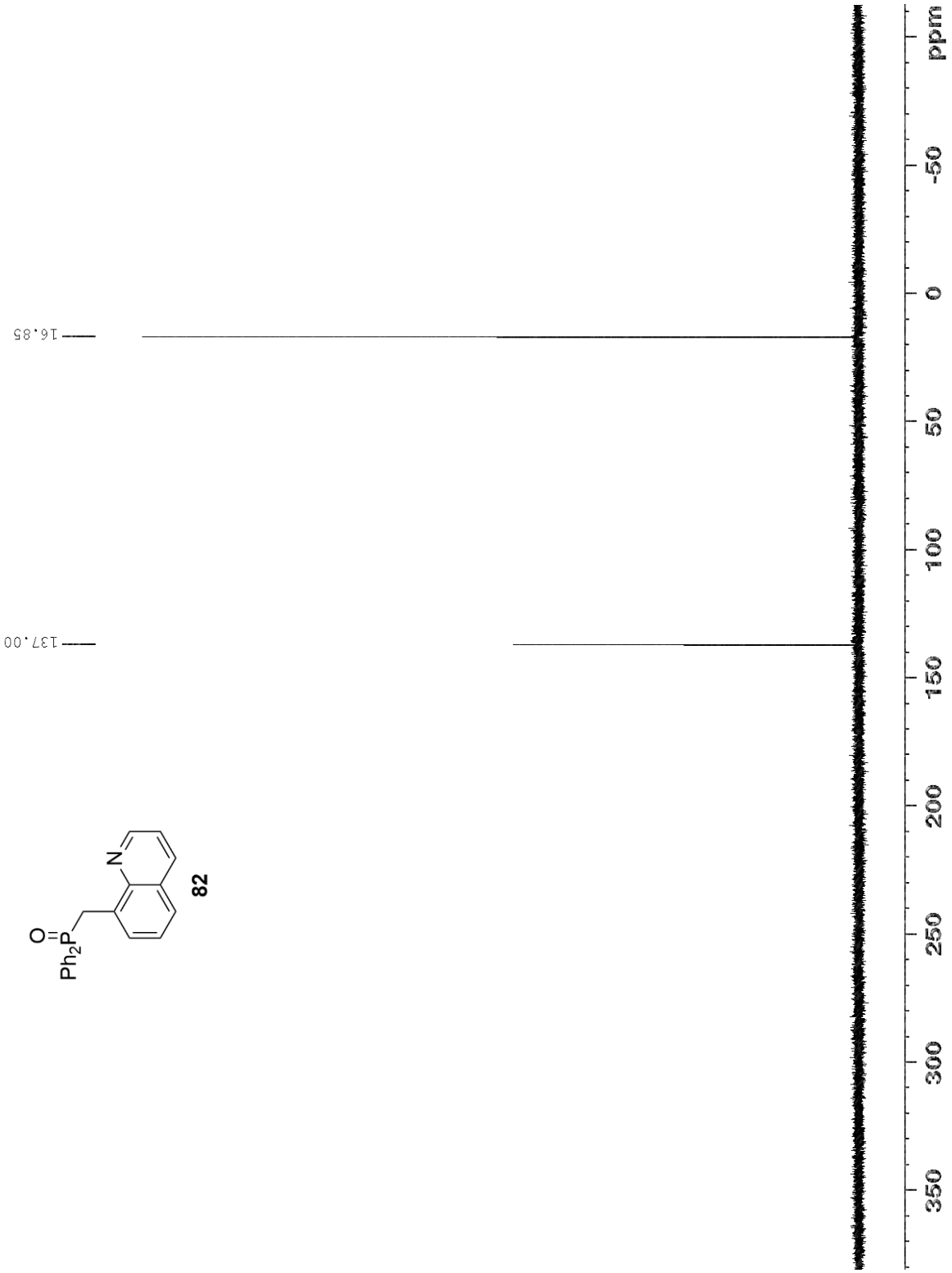


Figure 14. $^{31}P\{^{1}H\}$ NMR spectrum of aminophosphine **82**.

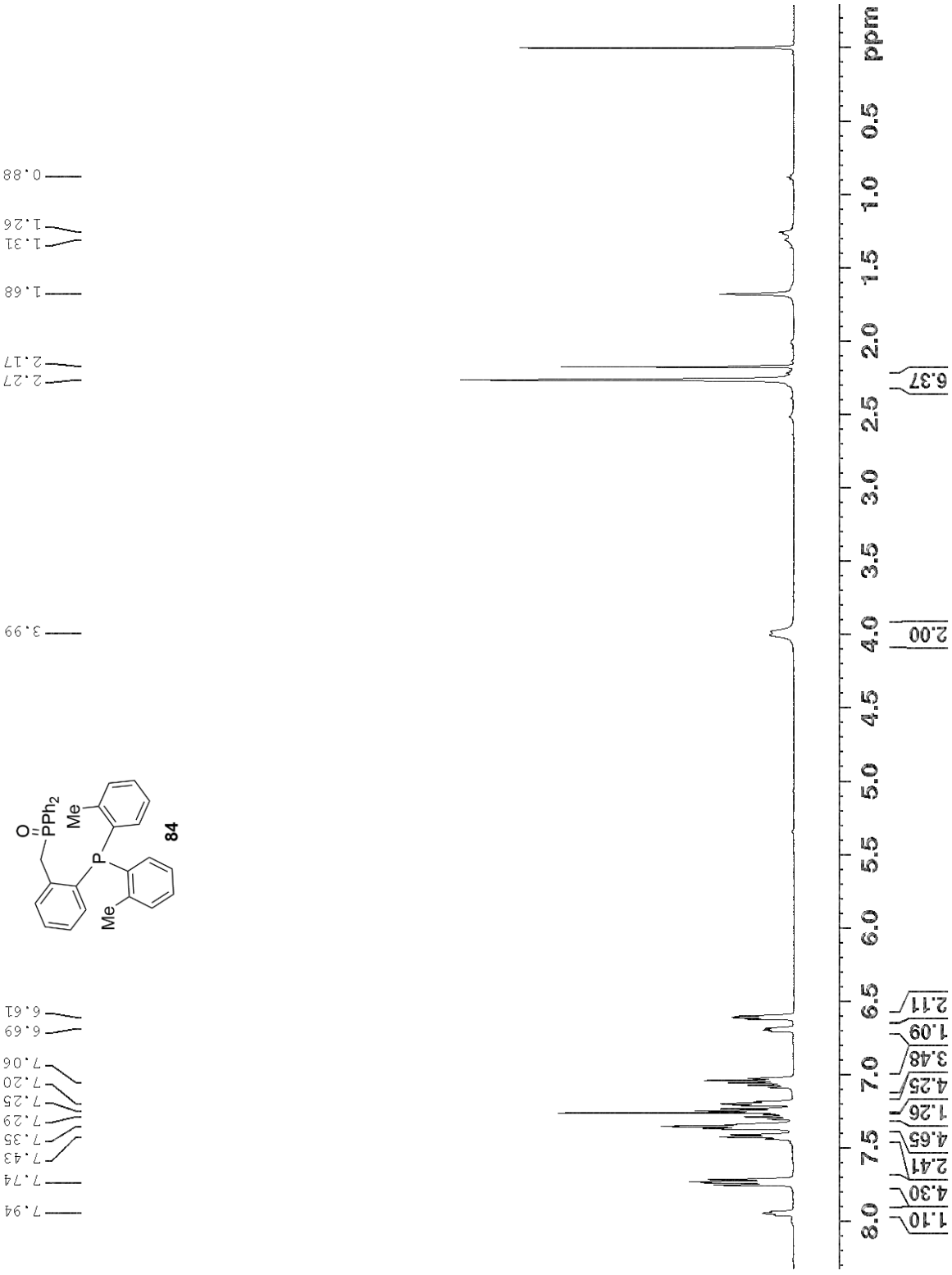


Figure 15**.** [1]H NMR spectrum of diphosphine oxide **84**.

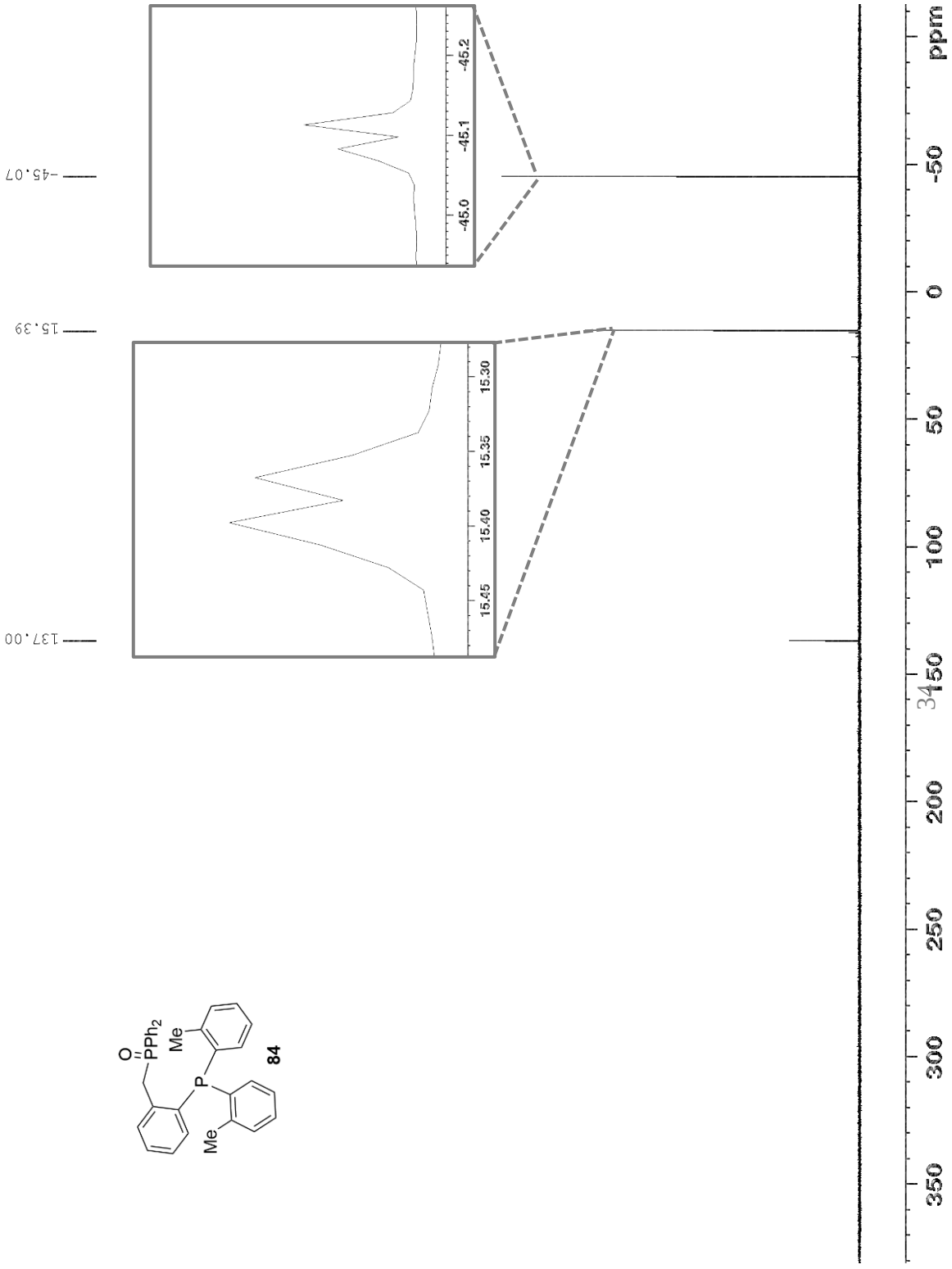


Figure 16. $^{1}P\{^{1}H\}$ NMR spectrum of diphosphine oxide **84**.

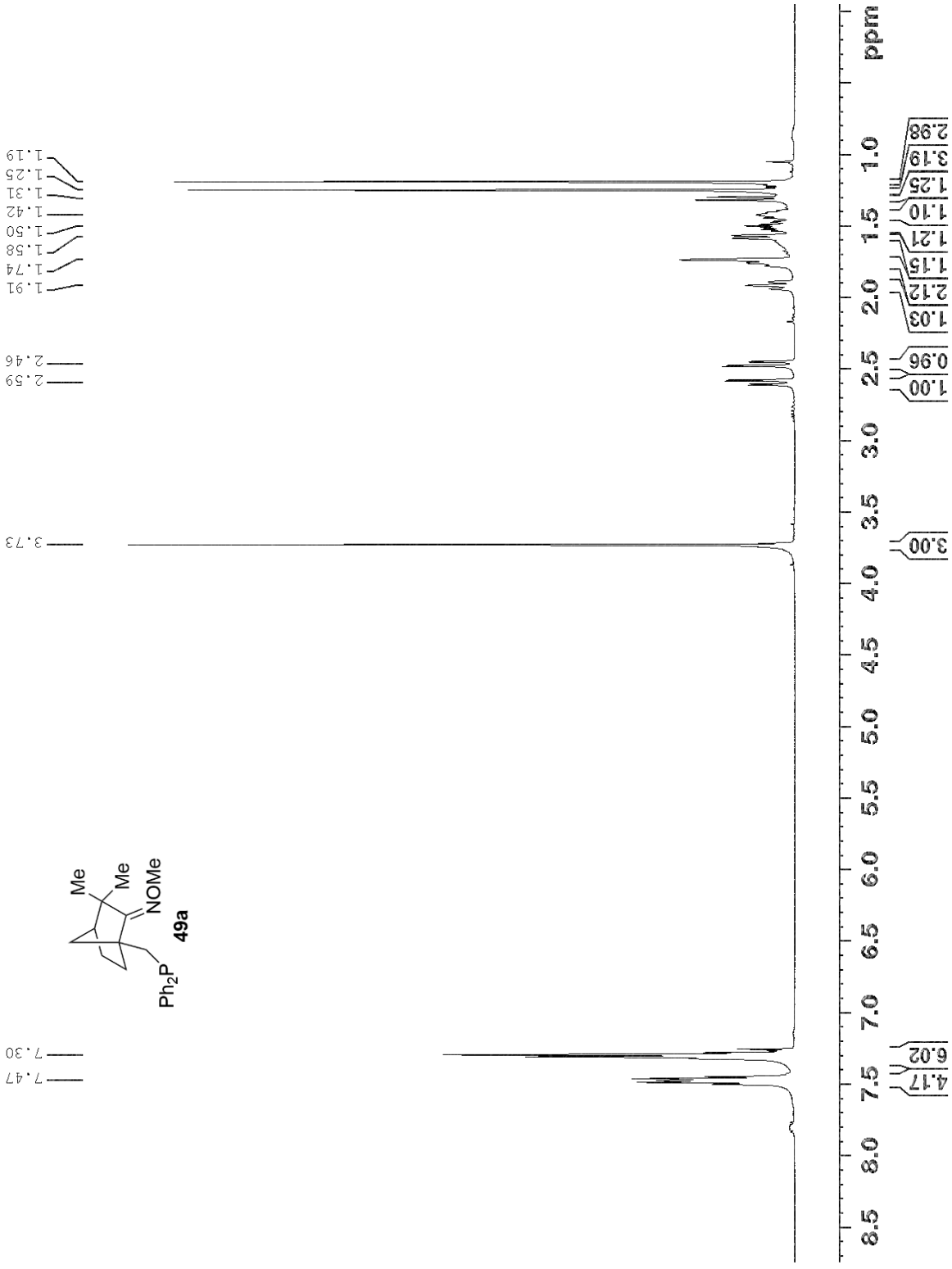


Figure 17. ^{1}H NMR spectrum of oximophosphine **49a**.

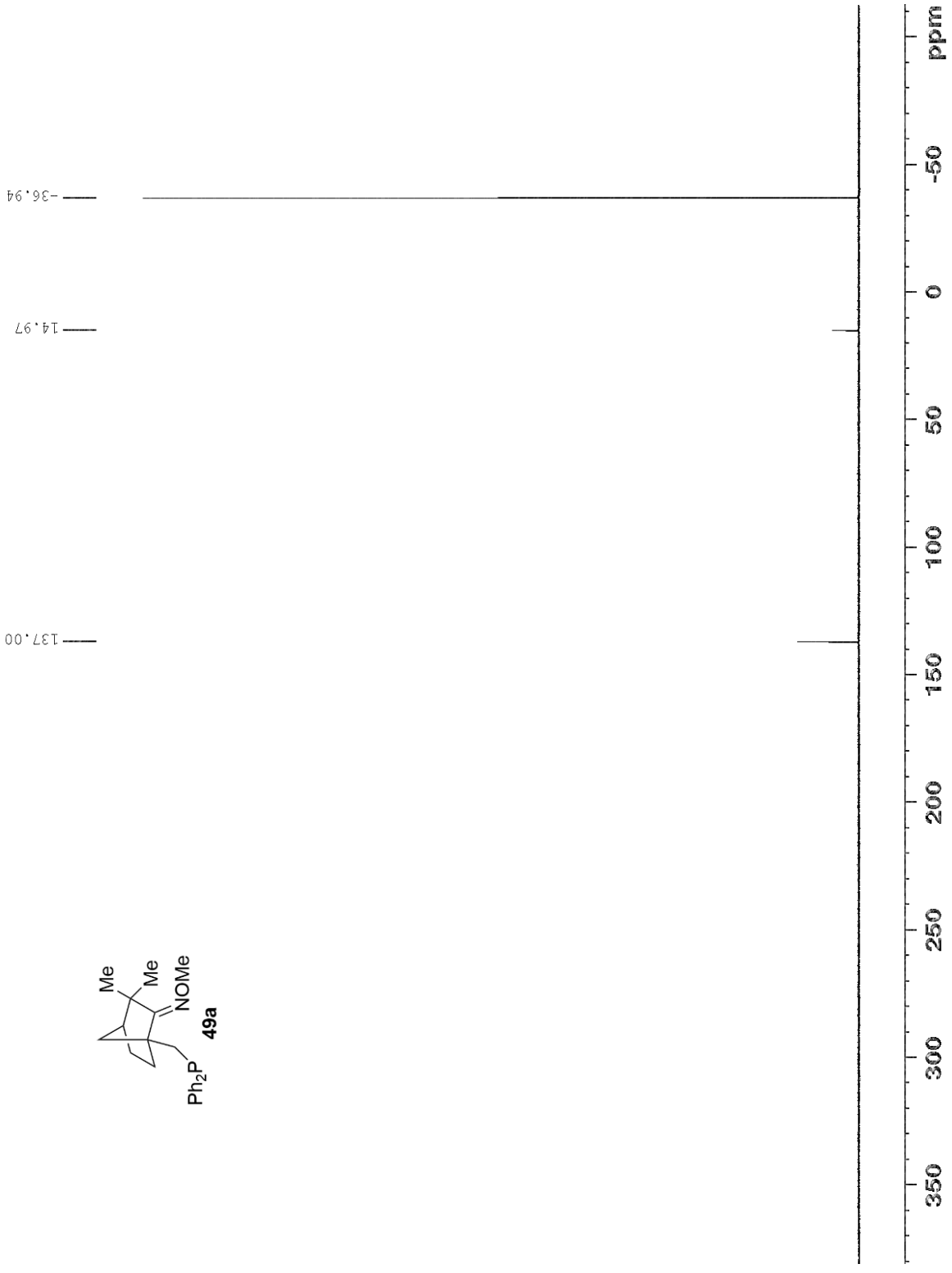


Figure 18. $^{31}P\{^{1}H\}$ NMR spectrum of oximophosphine **49a**.

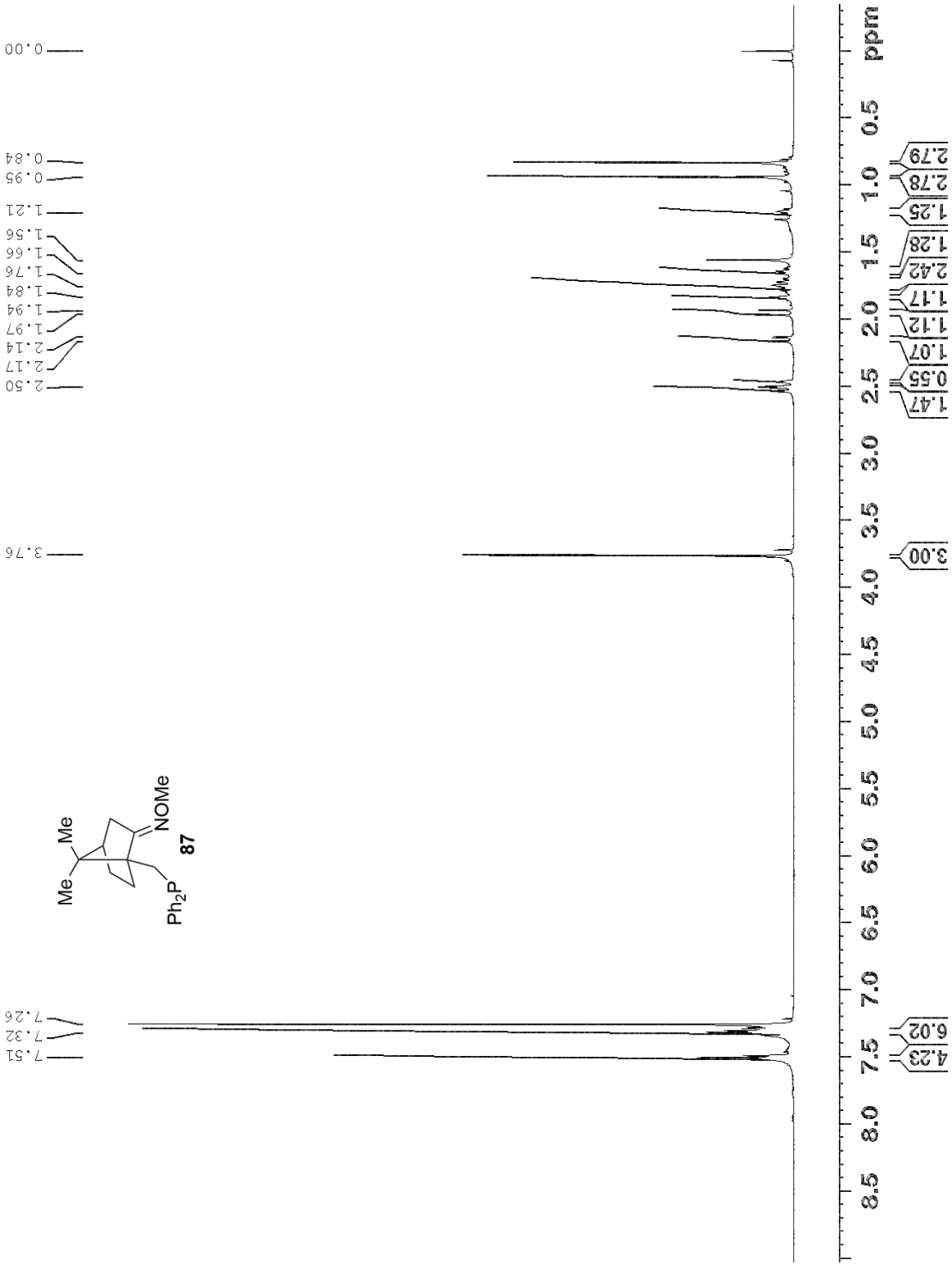


Figure 19. ^{1}H NMR spectrum of oximophosphine **87**.

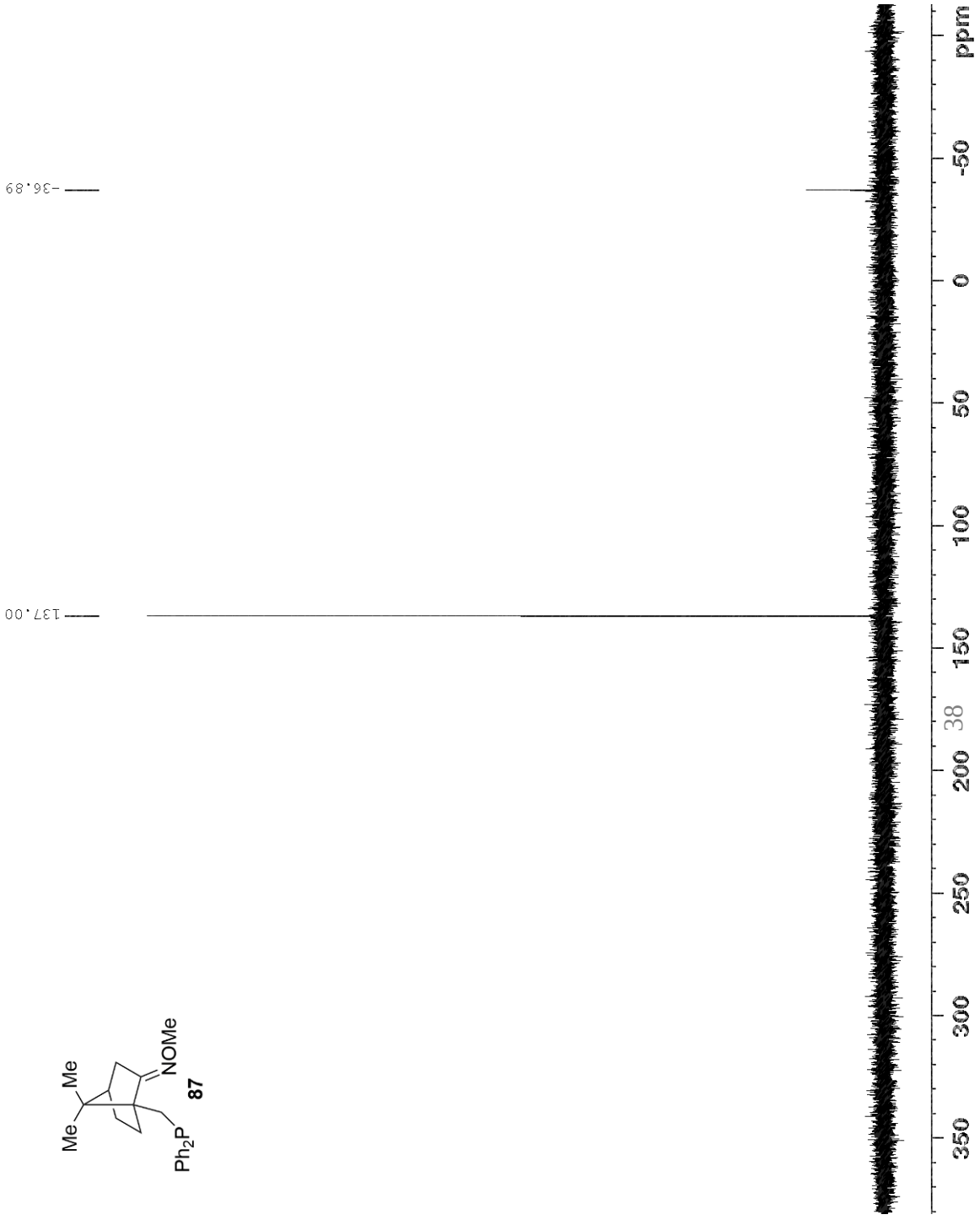


Figure 20. $^{31}P\{^{1}H\}$ NMR spectrum of oximophosphine **87**.

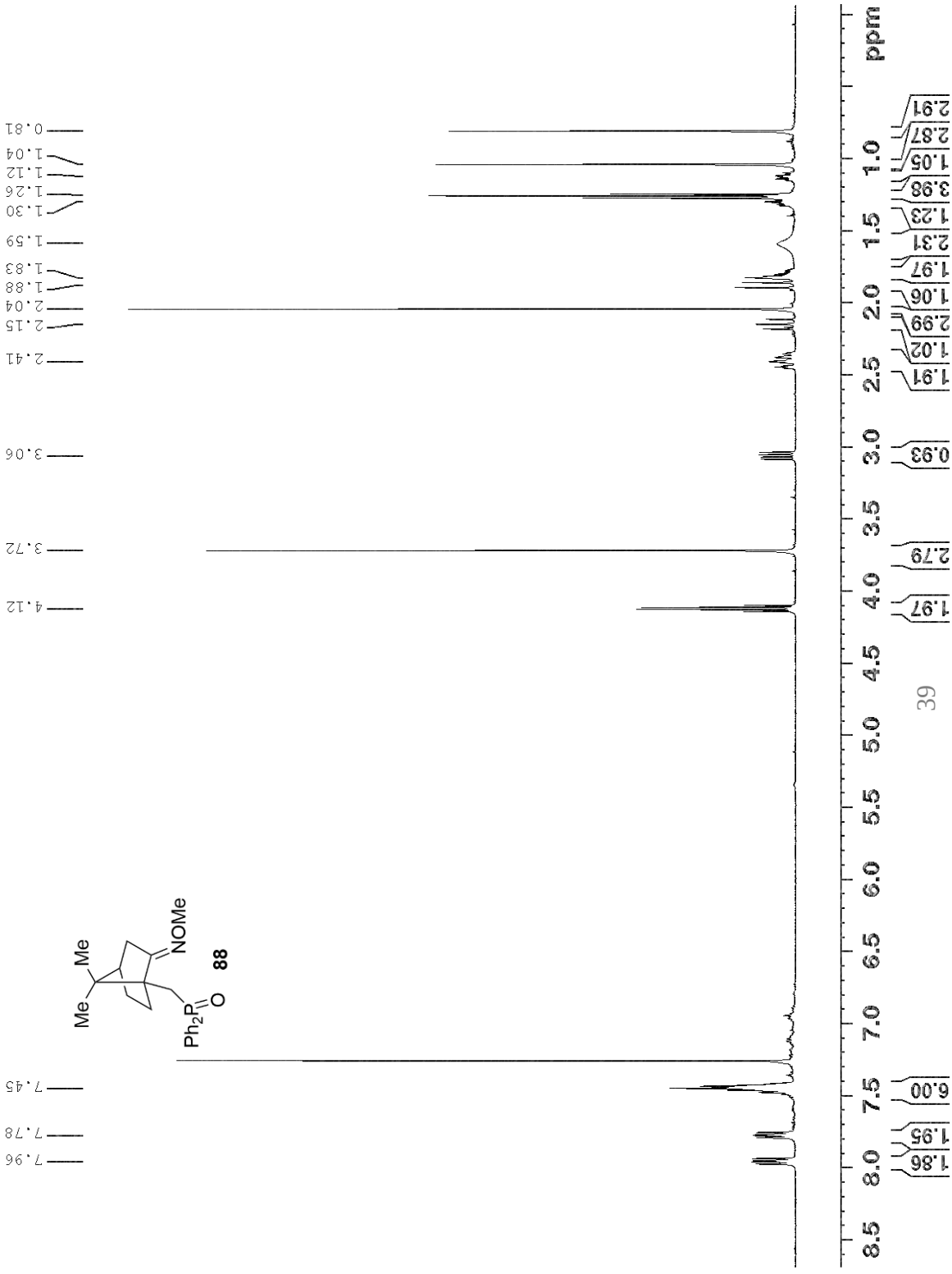


Figure 21. ^{1}H NMR spectrum of oximophosphine oxide **88**.

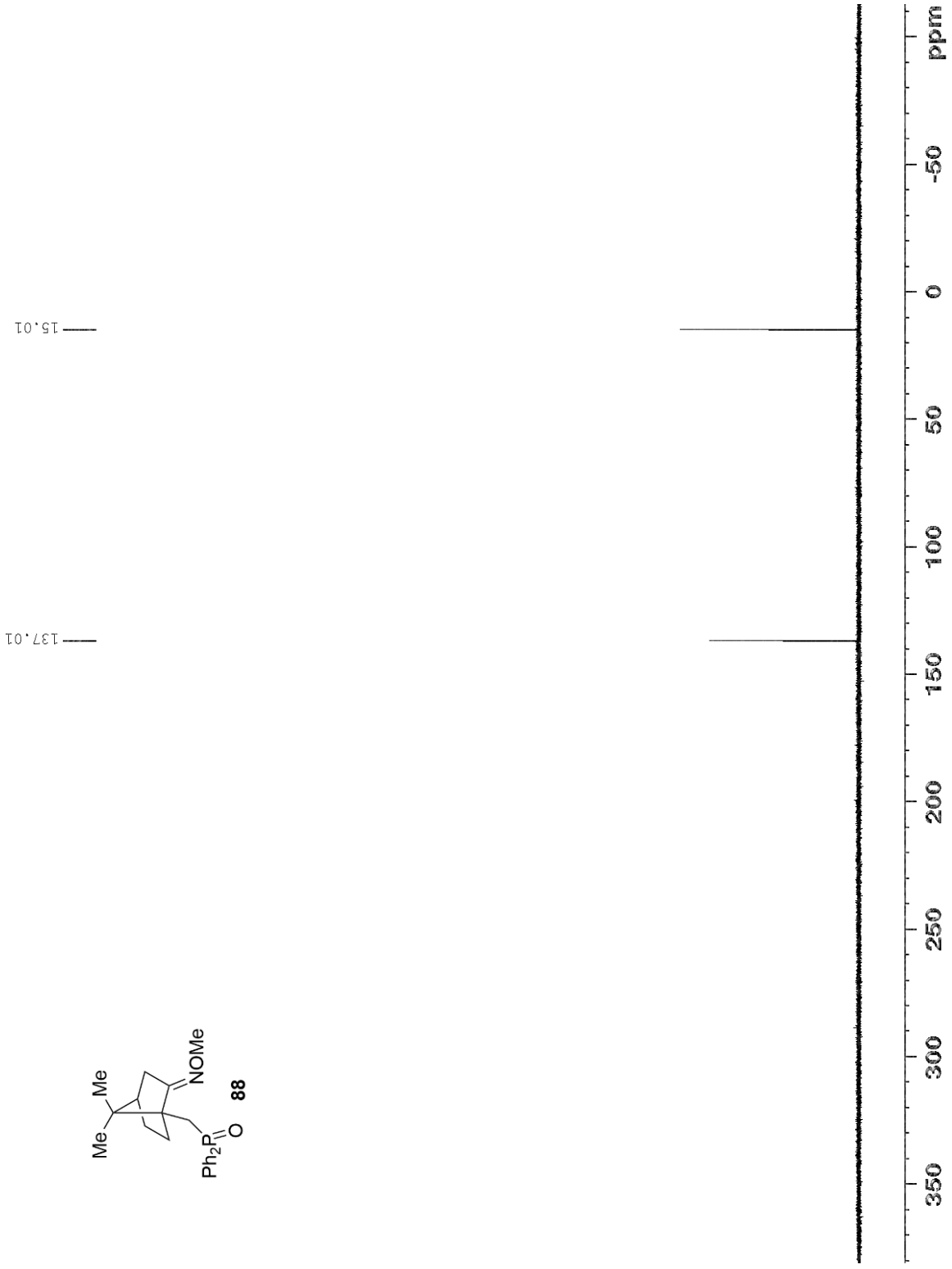


Figure 22. $^{31}P\{^{1}H\}$ NMR spectrum of oximophosphine oxide **88**.

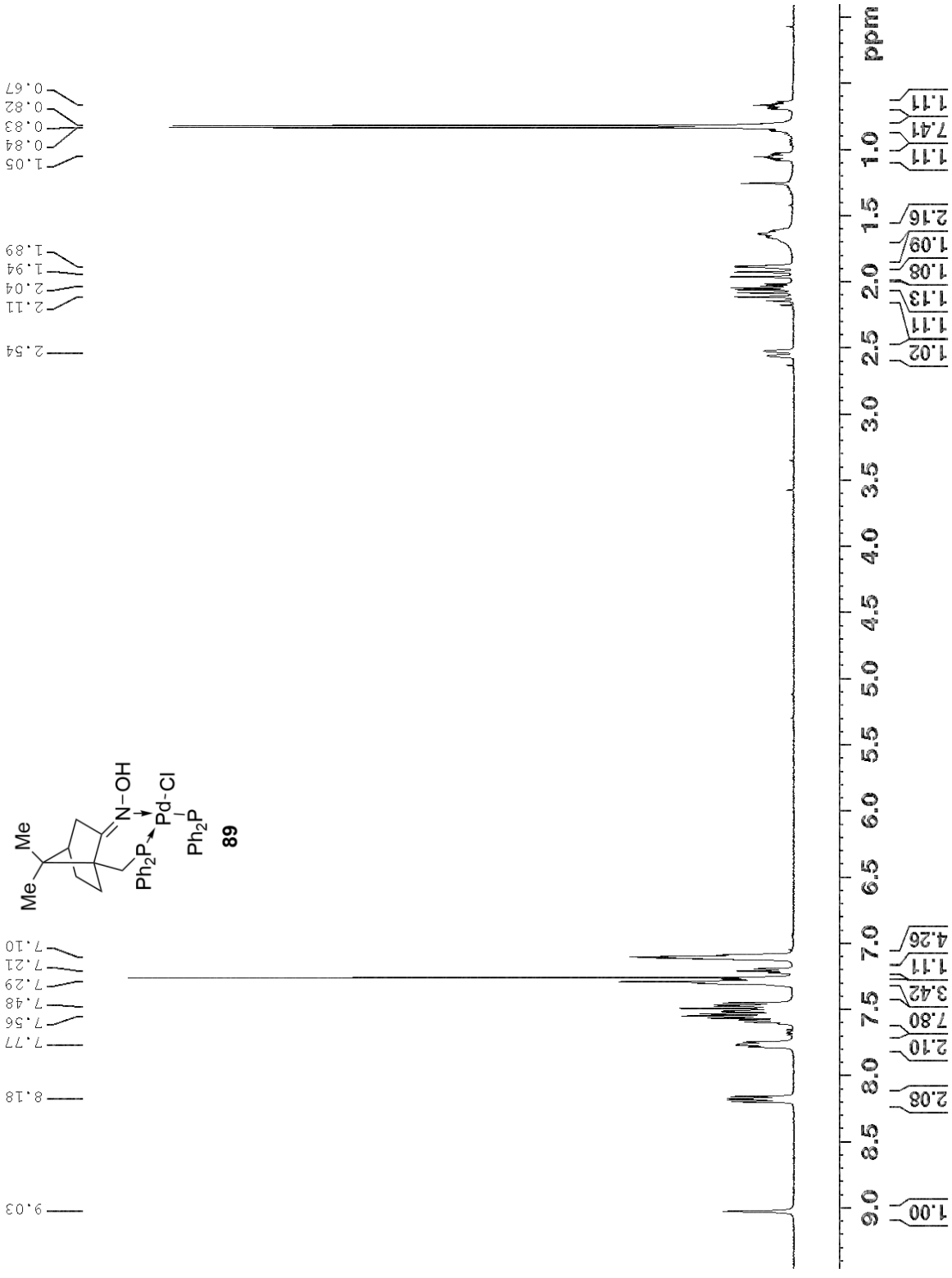


Figure 23. ^{1}H NMR spectrum of terminal phosphido complex **89**.

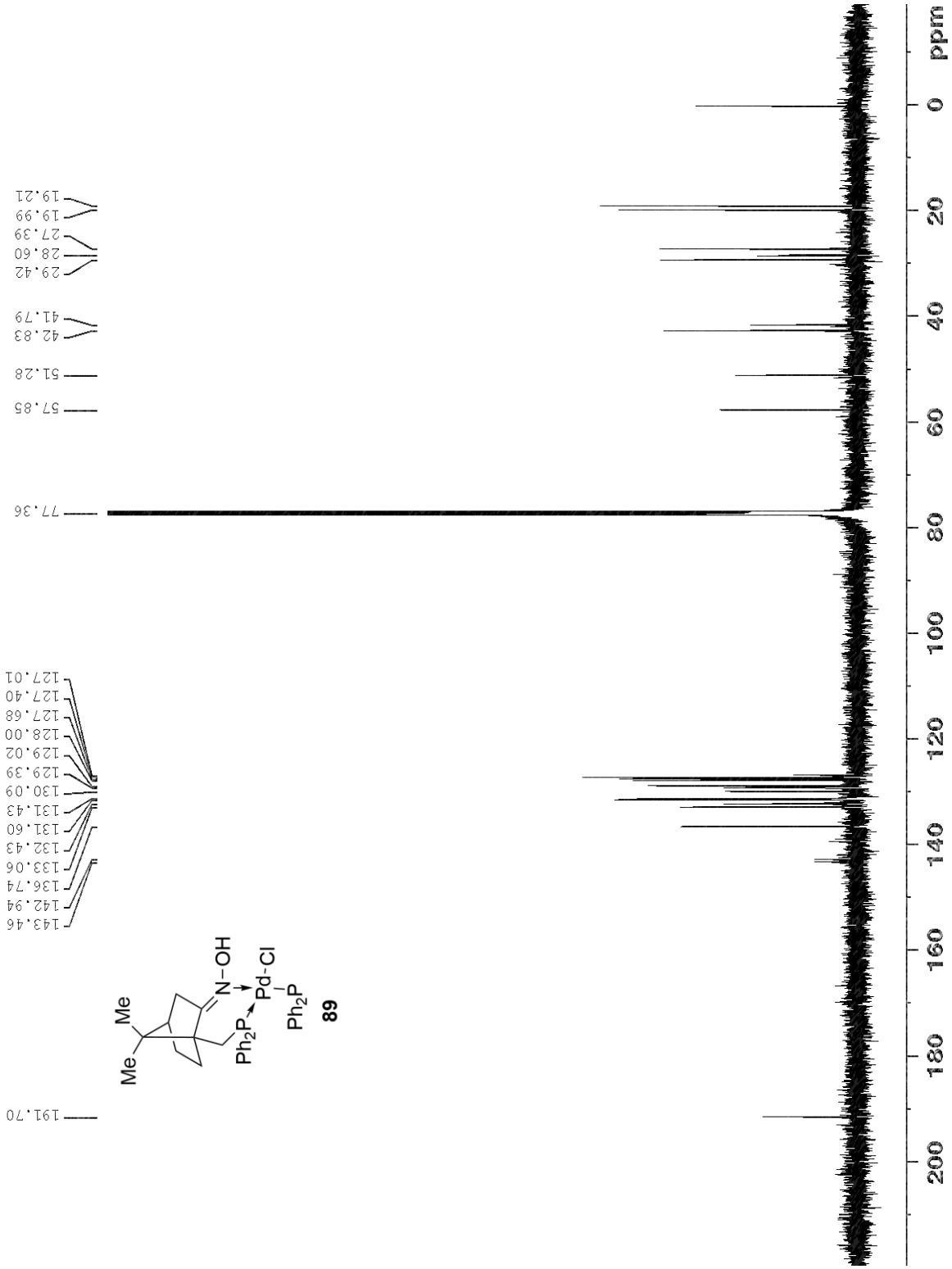


Figure 24. $^{13}C\{^{1}H\}$ NMR spectrum of terminal phosphido complex **89**.

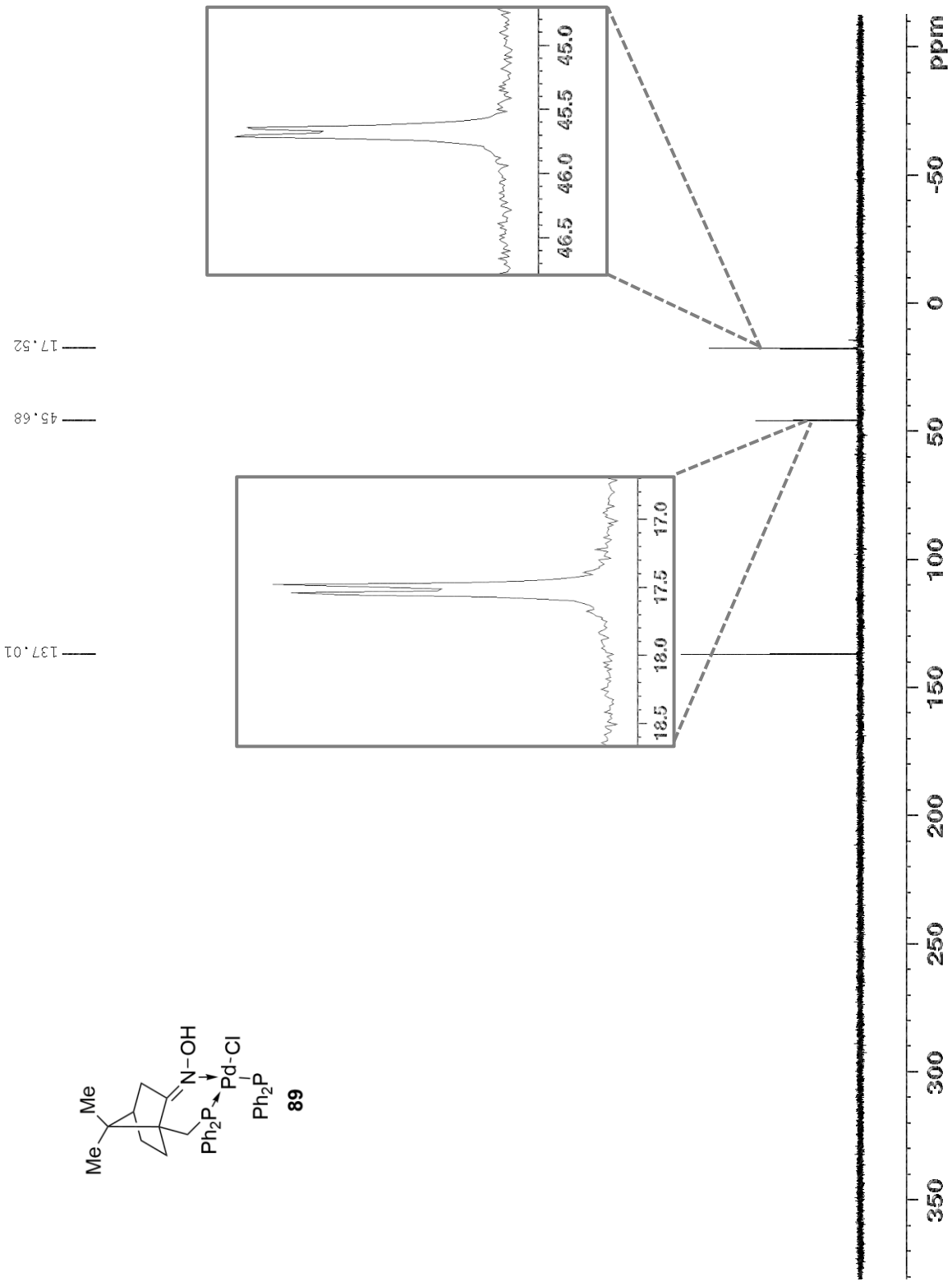


Figure 25. $^{31}P\{^{1}H\}$ NMR spectrum of terminal phosphido complex **89**.

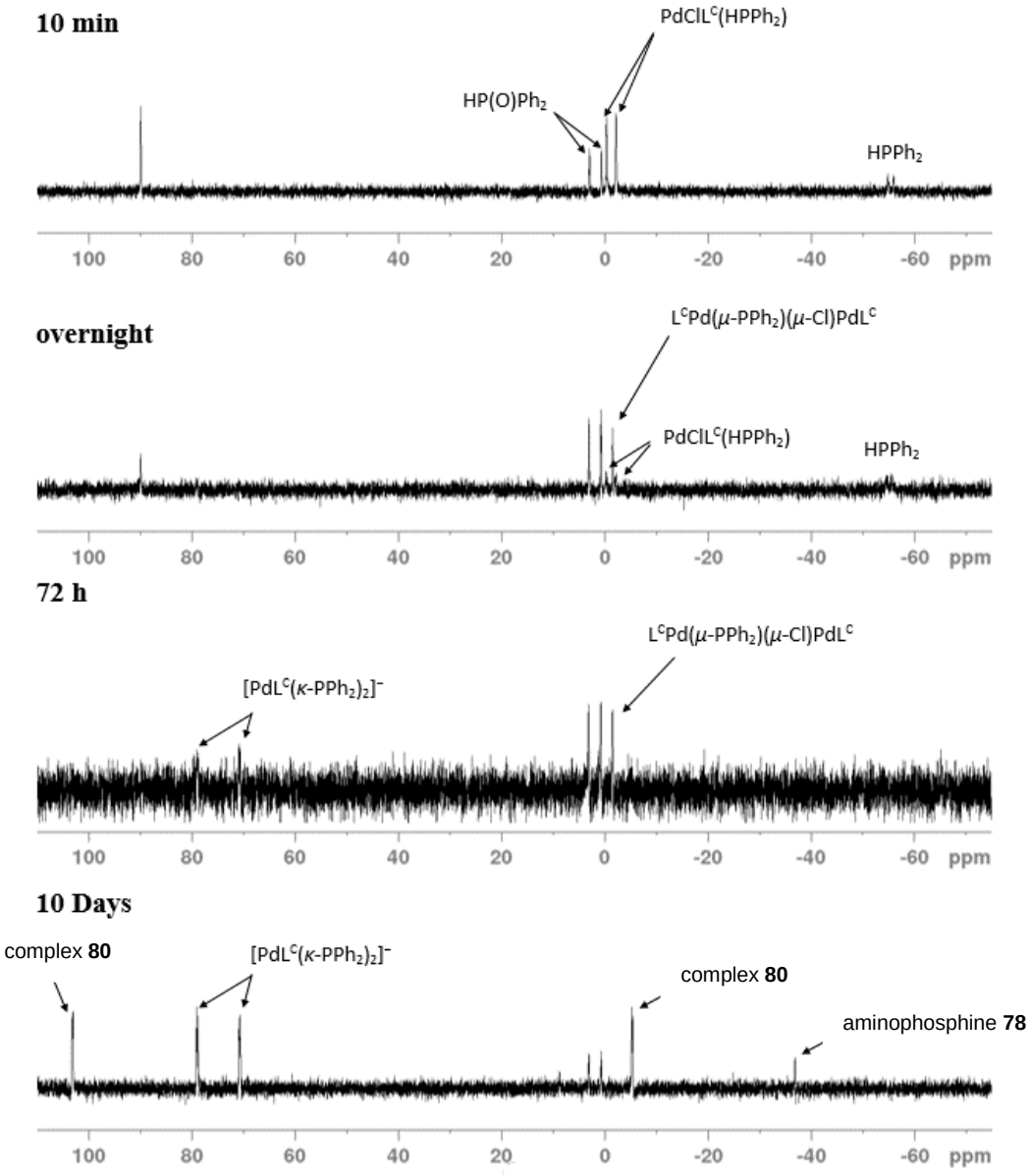

10 min
PdClL^C(HPPh2)
HP(O)Ph2
HPPh2
100 80 60 40 20 0 -20 -40 -60 ppm
overnight
L^CPd(μ-PPh2)(μ-Cl)PdL^C
PdClL^C(HPPh2)
HPPh2
100 80 60 40 20 0 -20 -40 -60 ppm
72 h
L^CPd(μ-PPh2)(μ-Cl)PdL^C
[PdL^C(κ-PPh2)2]^-
100 80 60 40 20 0 -20 -40 -60 ppm
10 Days
complex 80
[PdL^C(κ-PPh2)2]^-
complex 80
aminophosphine 78
100 80 60 40 20 0 -20 -40 -60 ppm

Figure 26. ^{31}P NMR spectra of 2.5 equivalents $HPPh_2$/CPC **77**/Cs_2CO_3 in toluene-d_8 frozen to –95 °C and recorded at rt. (L^C = cyclopalladated 2-*tert*-butyl-4,4-dimethyl-2-oxazoline)

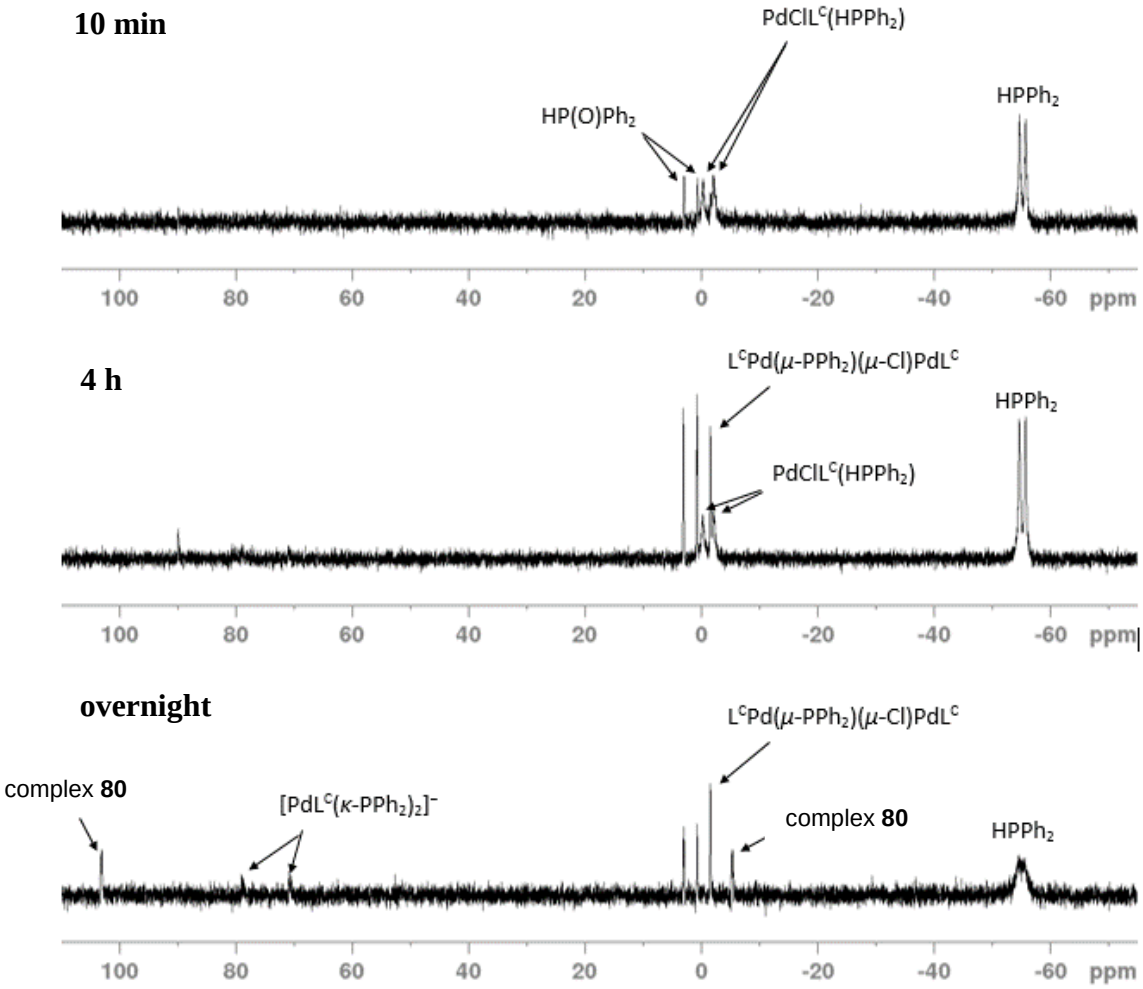


Figure 27. ^{31}P NMR spectra of 4.5 equivalents $HPPh_2$/CPC **77**/Cs_2CO_3 in toluene-d_8 frozen to –95 °C and recorded at rt. (L^C = 2-*tert*-butyl-4,4-dimethyl-2-oxazoline)

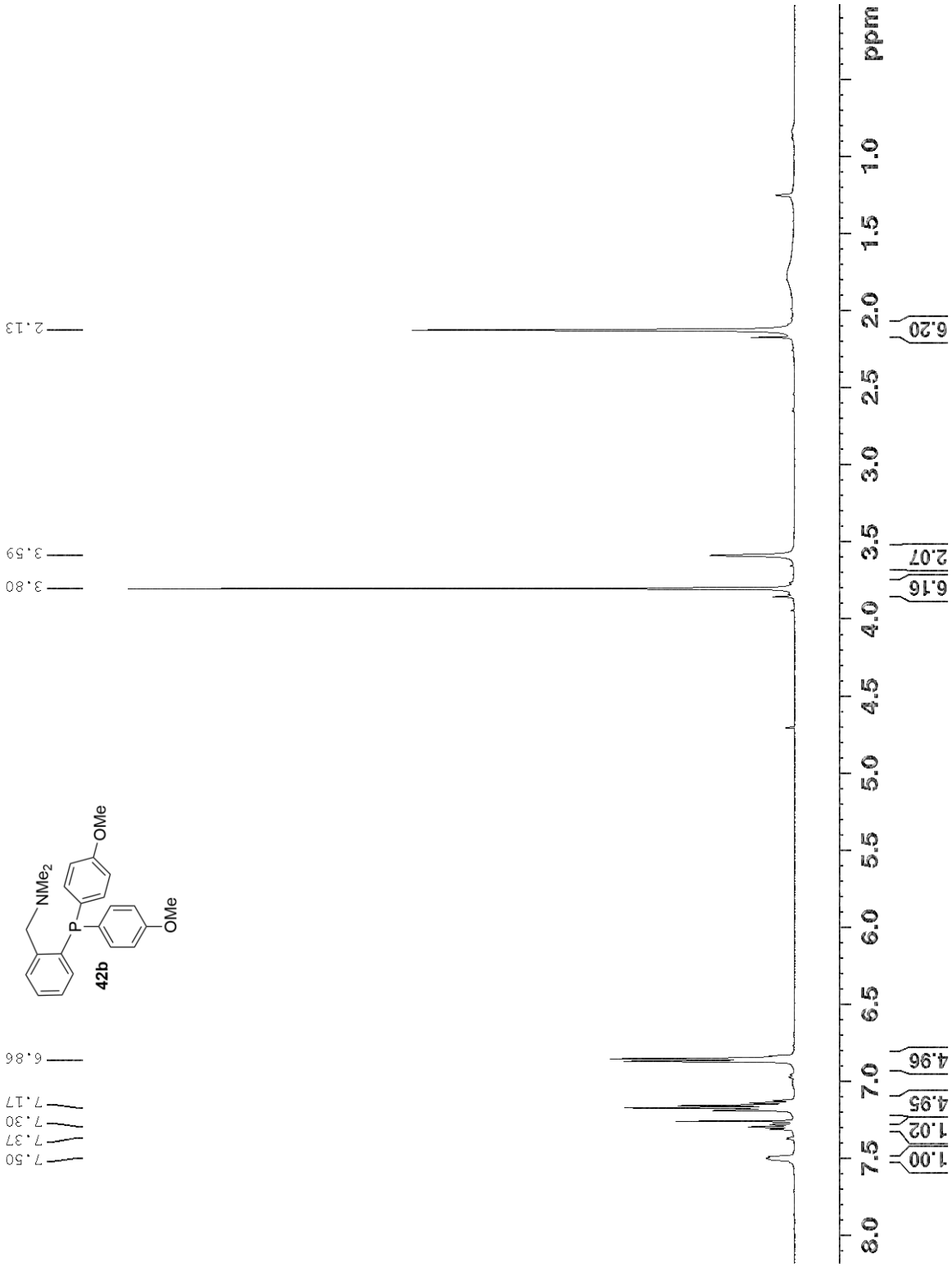


Figure 28. ^{1}H NMR spectrum of aminophosphine **42b**.

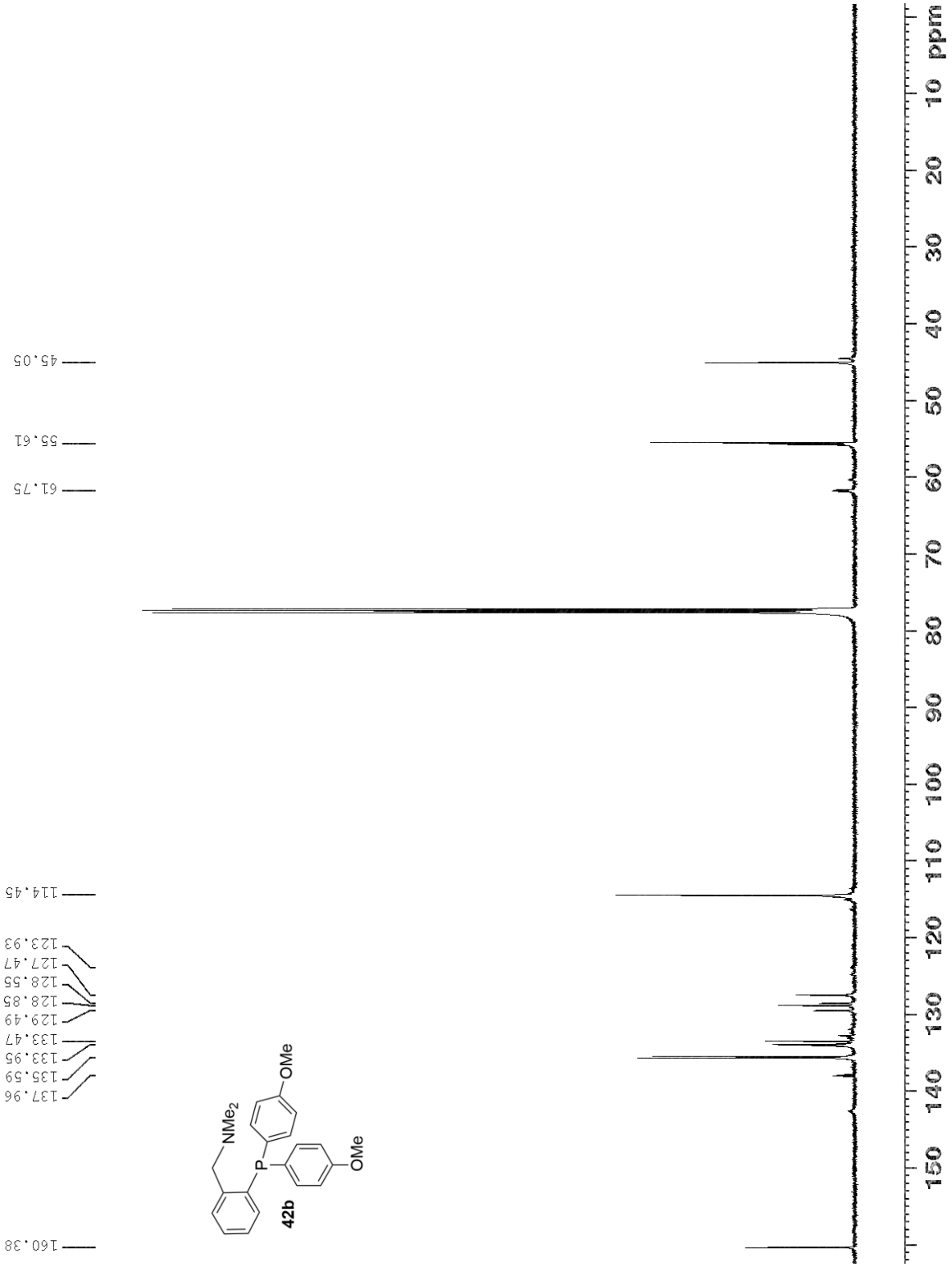


Figure 29. $^{13}C\{^{1}H\}$ NMR spectrum of aminophosphine **42b**.

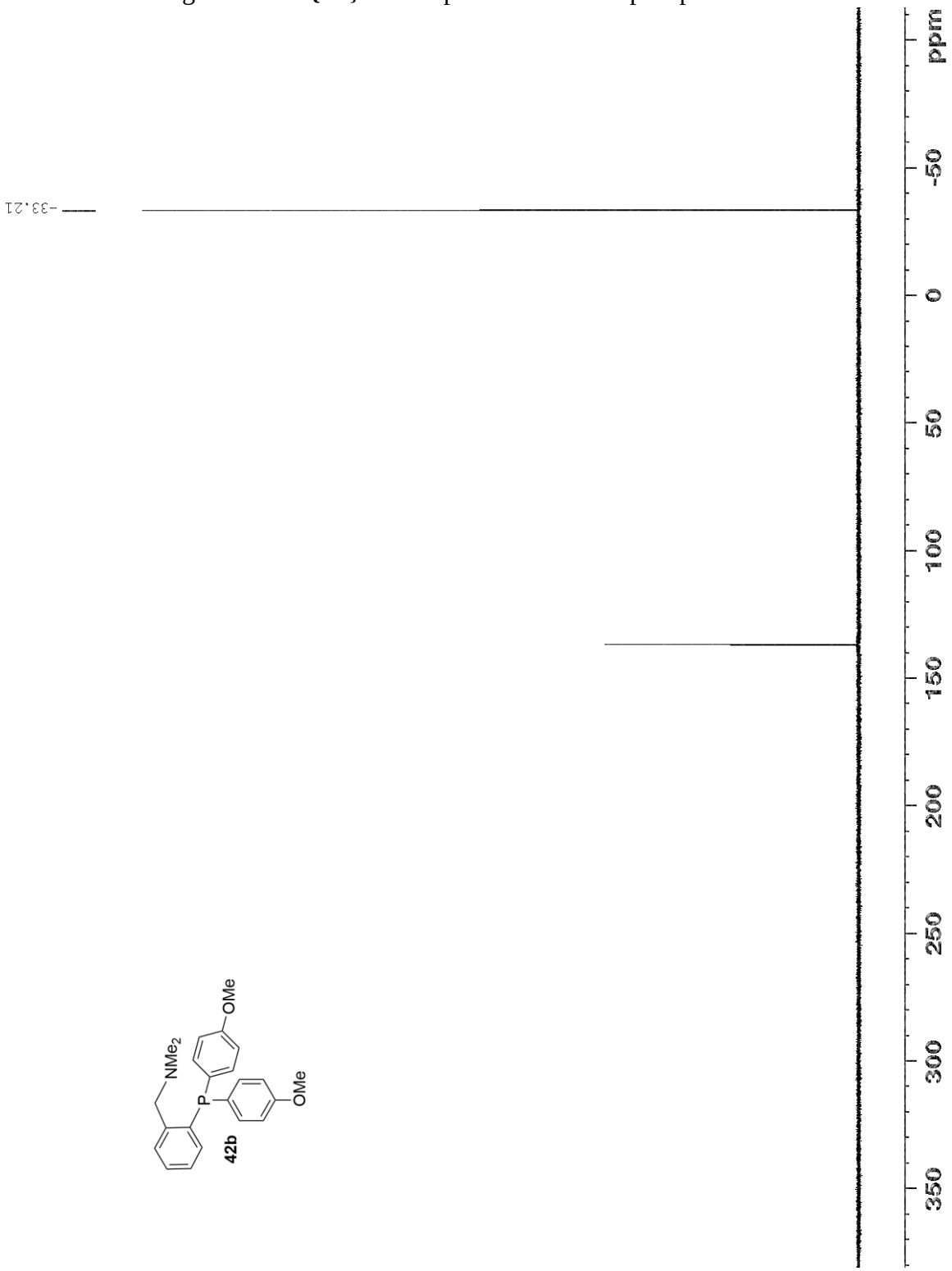


Figure 30. $^{31}P\{^{1}H\}$ NMR spectrum of aminophosphine **42b**.

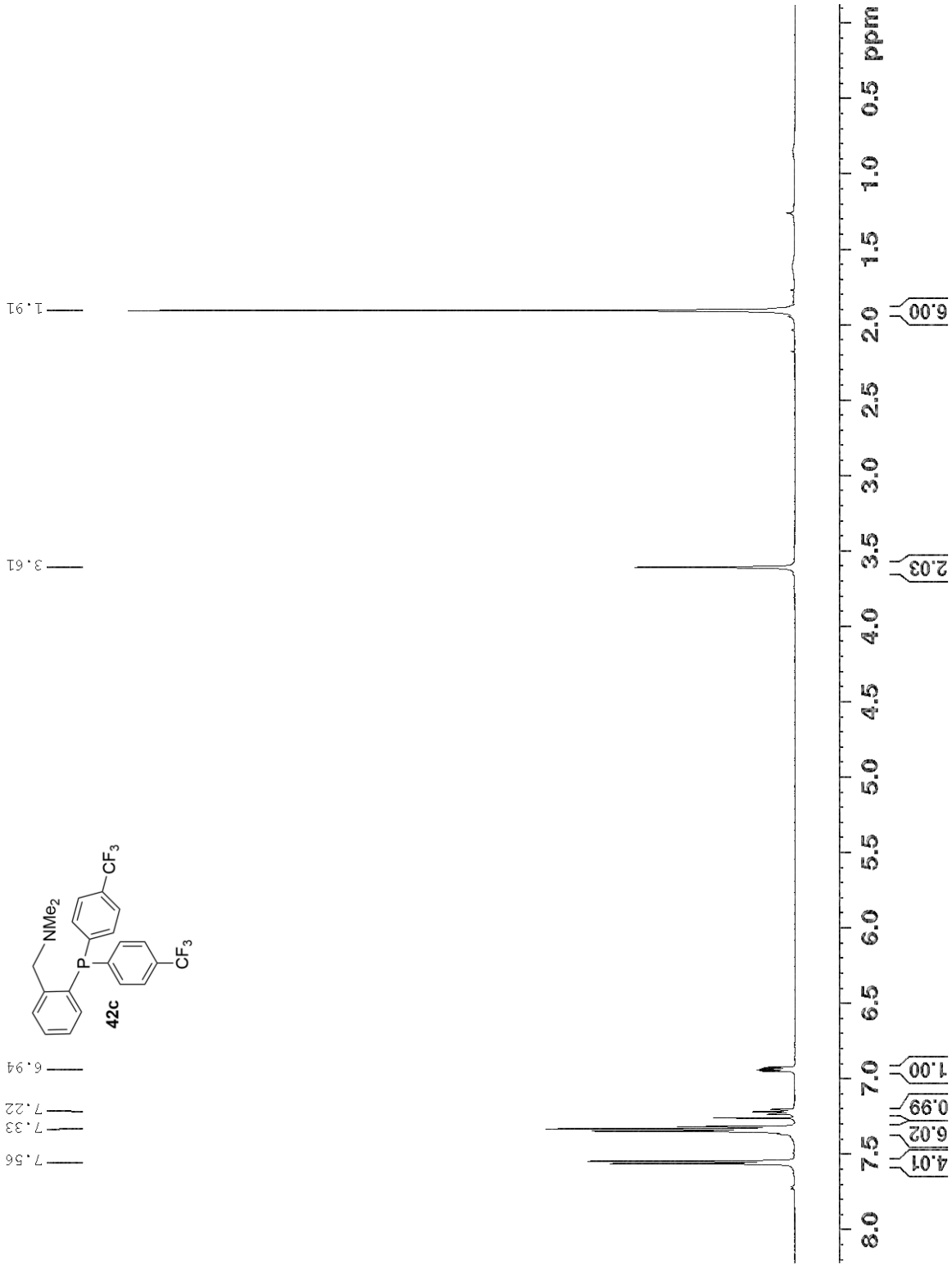


Figure 31. ^{1}H NMR spectrum of aminophosphine **42c**.

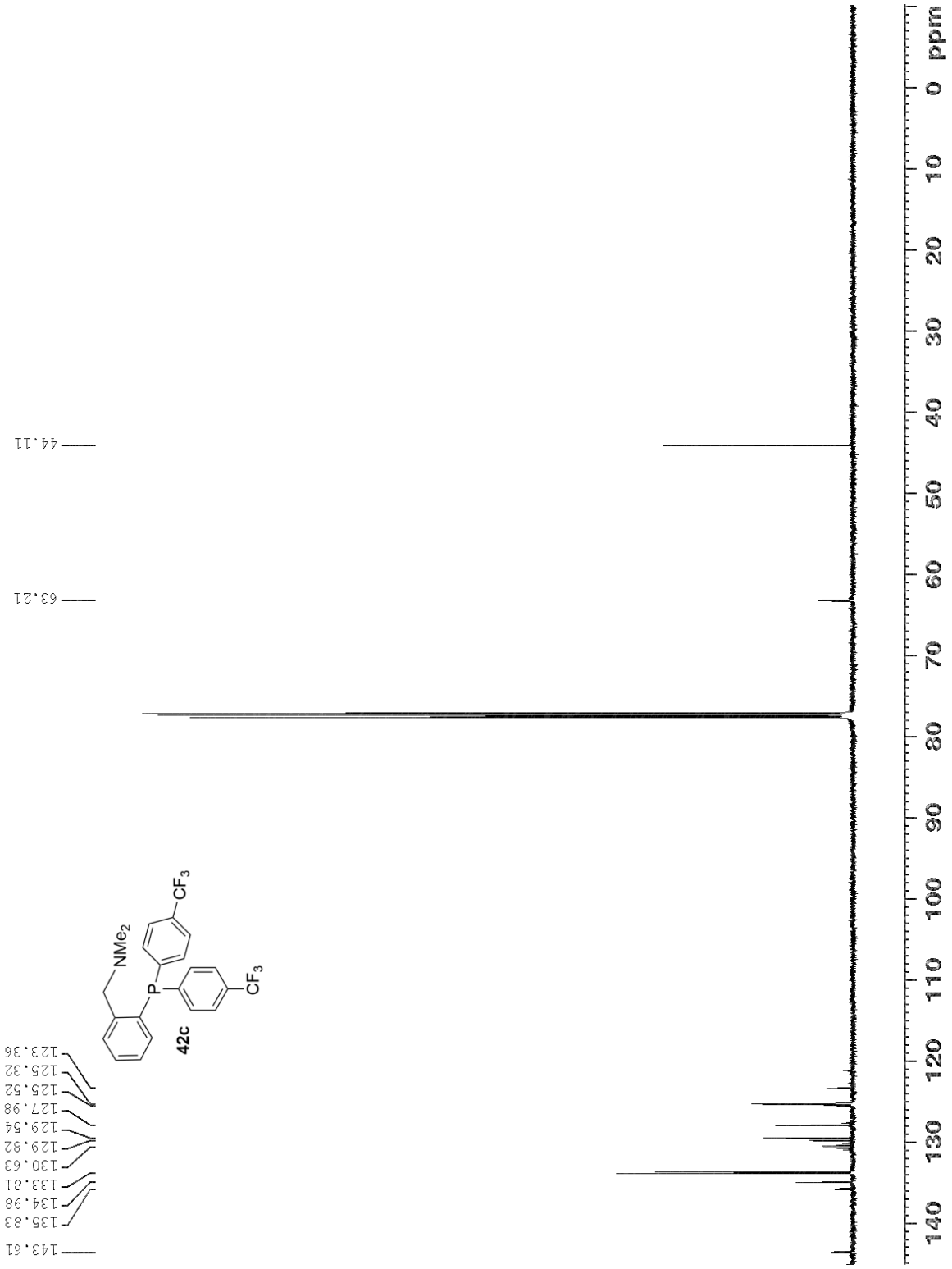


Figure 32. $^{13}C\{^{1}H\}$ NMR spectrum of aminophosphine **42c**.

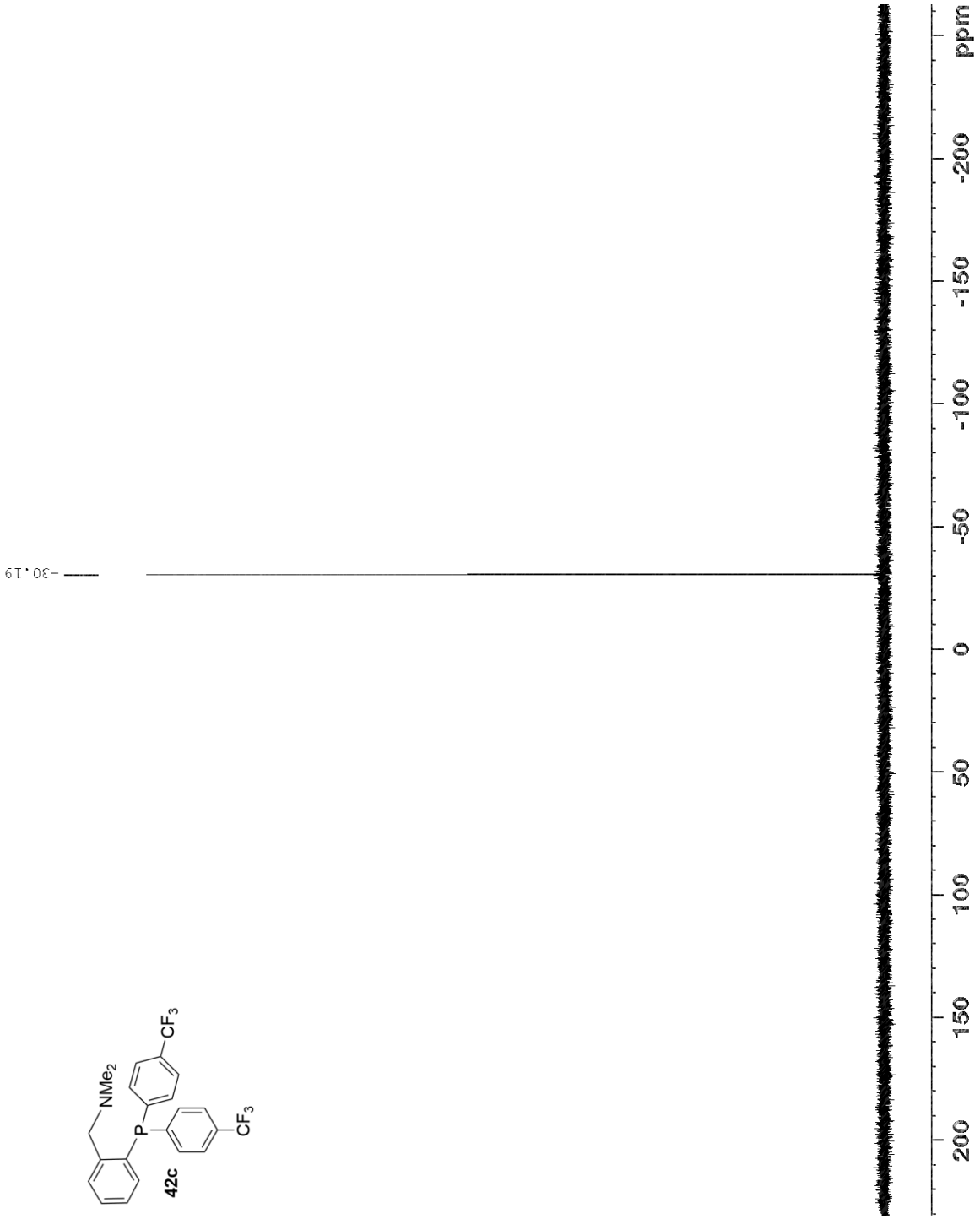


Figure 33. $^{31}P\{^{1}H\}$ NMR spectrum of aminophosphine **42c**.

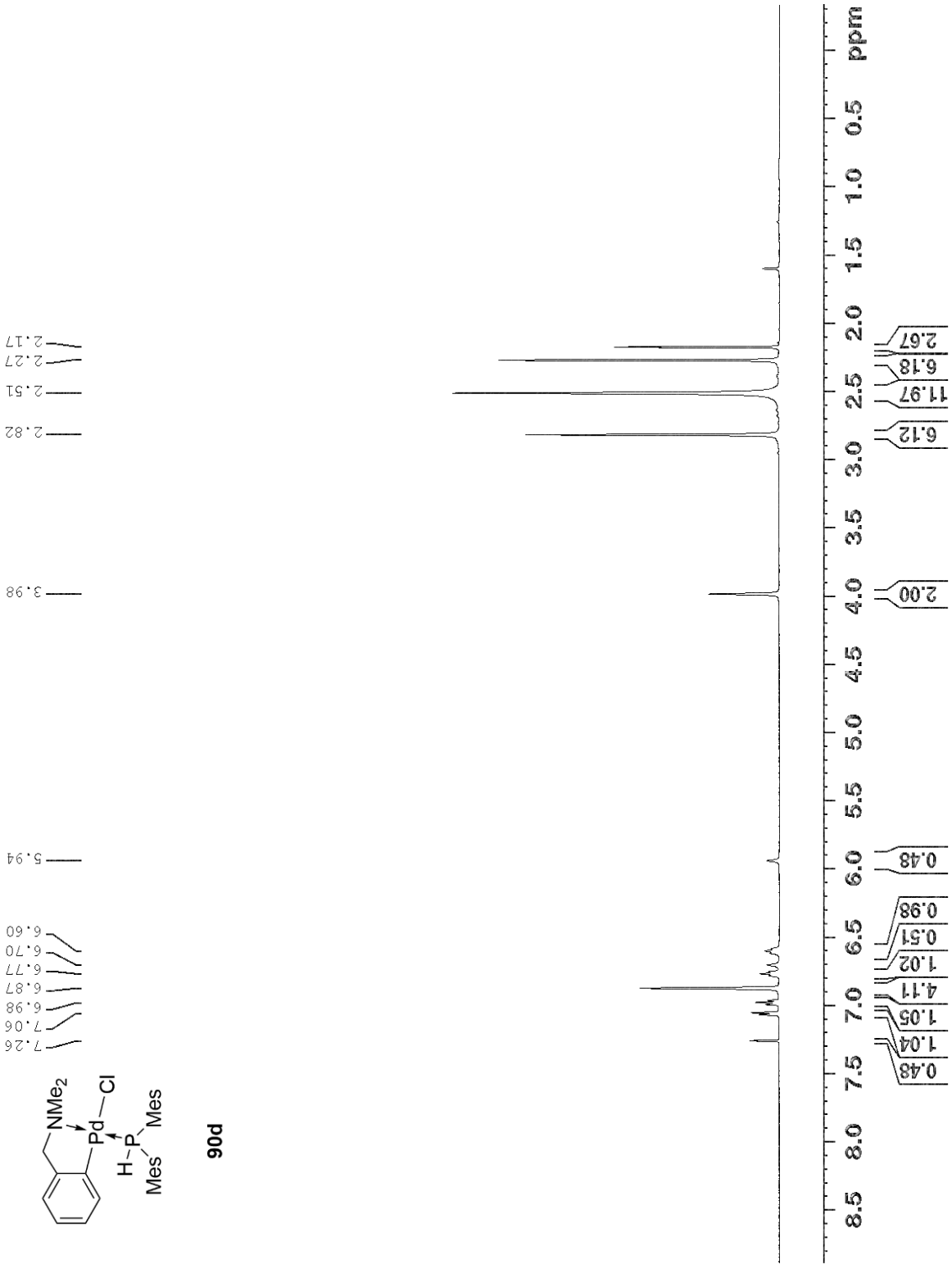


Figure 34. ^{1}H NMR spectrum of mononuclear complex **90d**.

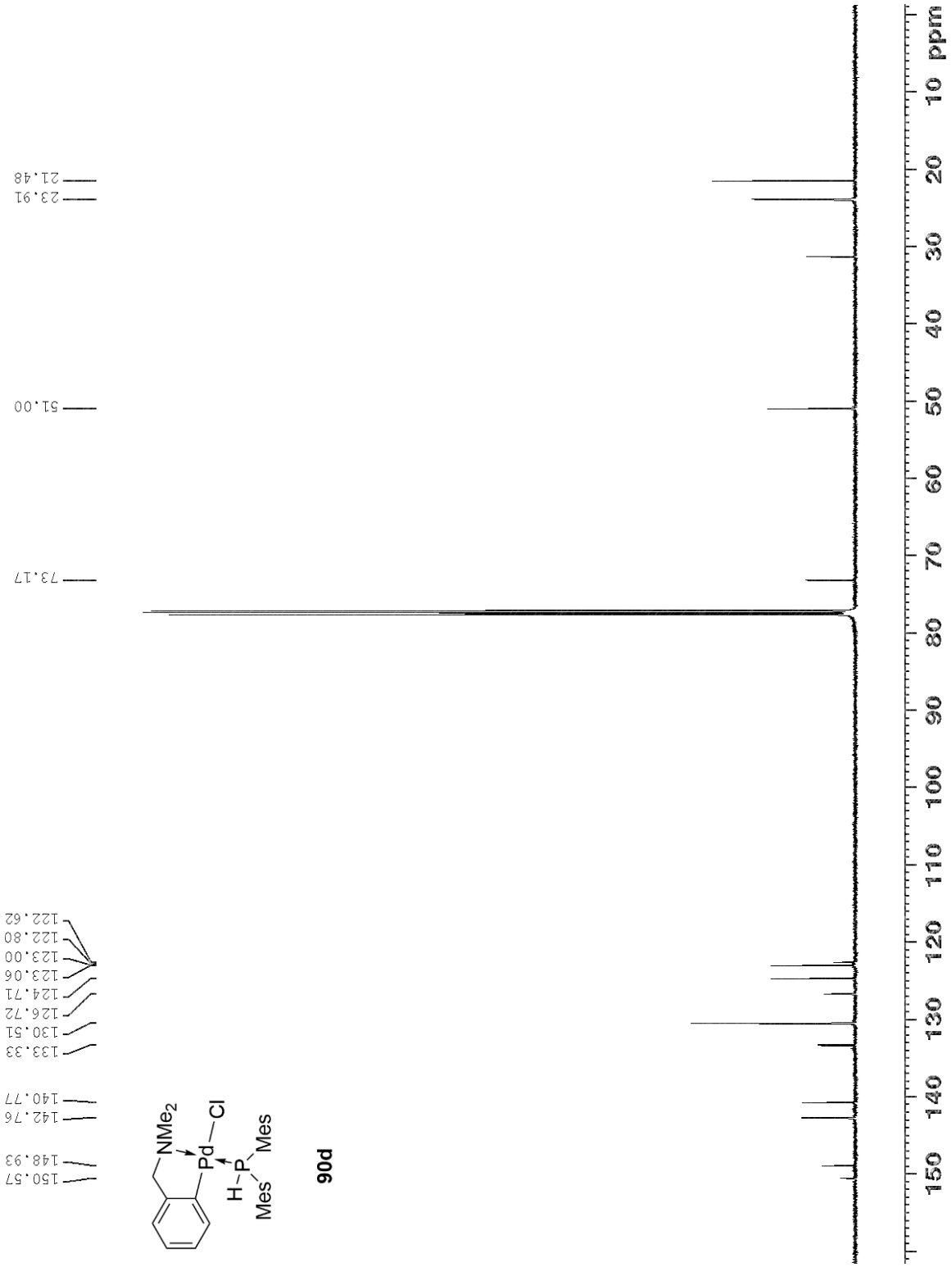


Figure 35. $^{13}C\{^{1}H\}$ NMR spectrum of mononuclear complex **90d**.

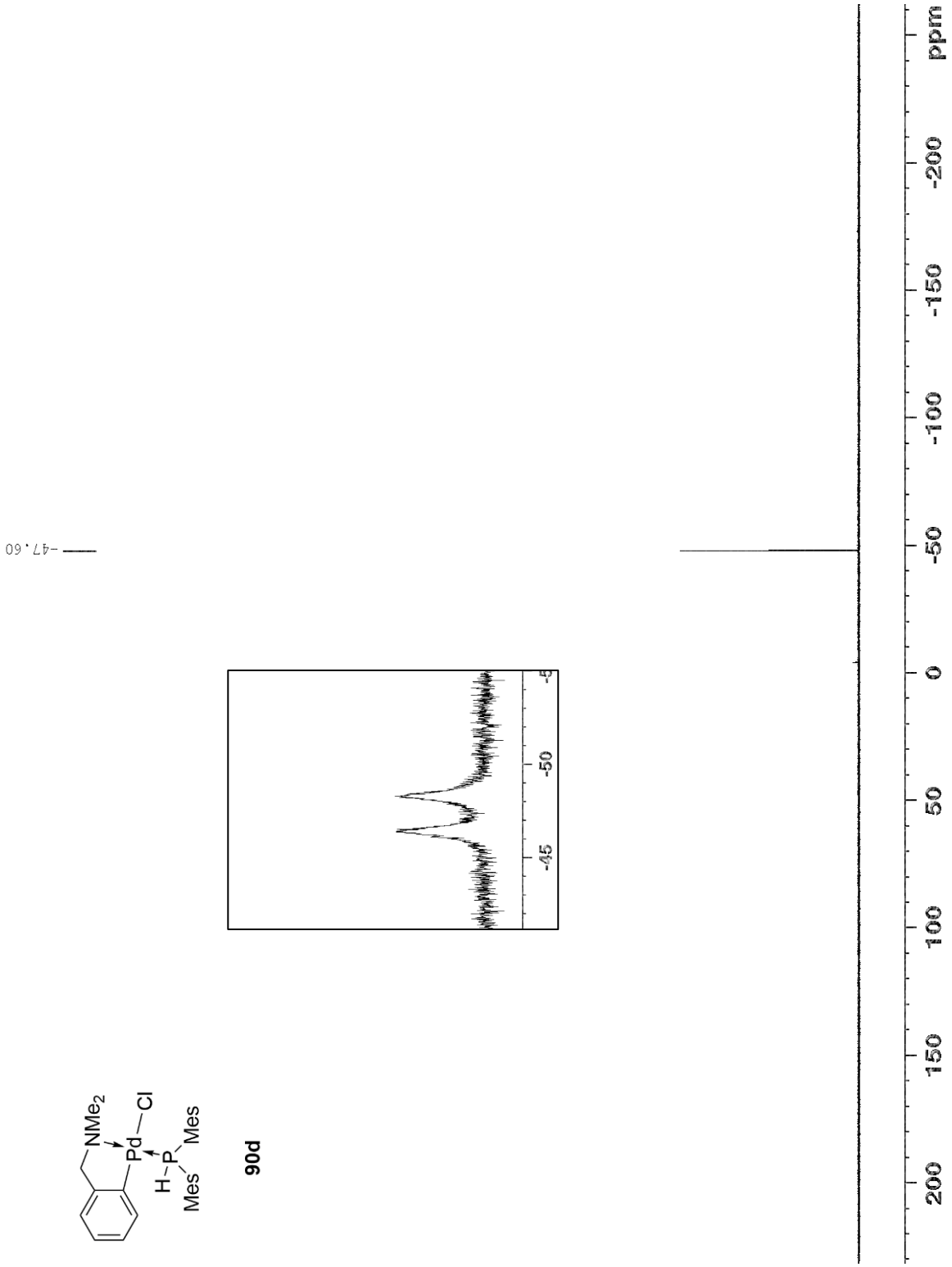


Figure 36. ^{31}P NMR spectrum of mononuclear complex **90d**. (Proton-coupled ^{31}P NMR signal in expansion.)

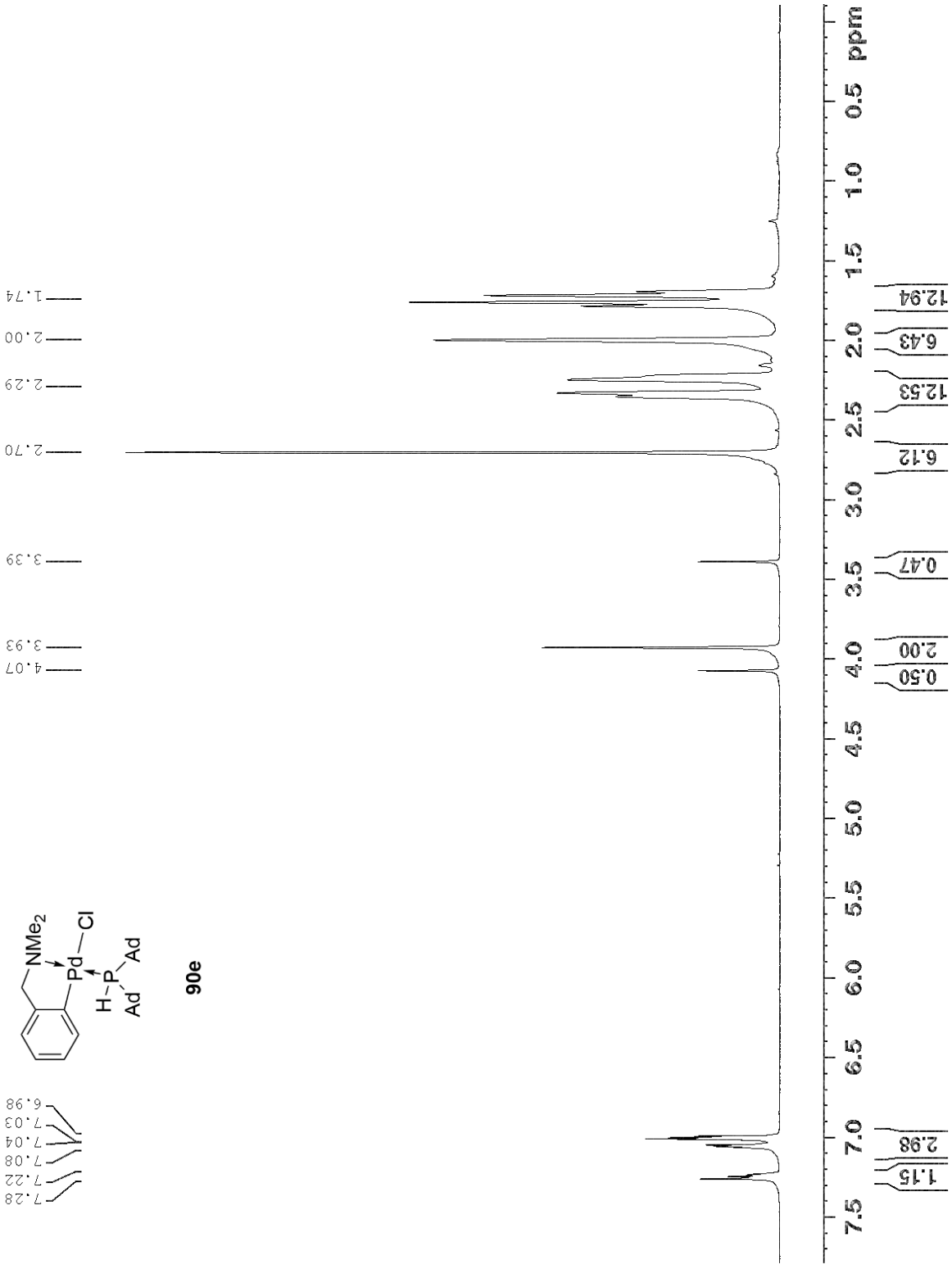


Figure 37. ^{1}H NMR spectrum of mononuclear complex **90e**.

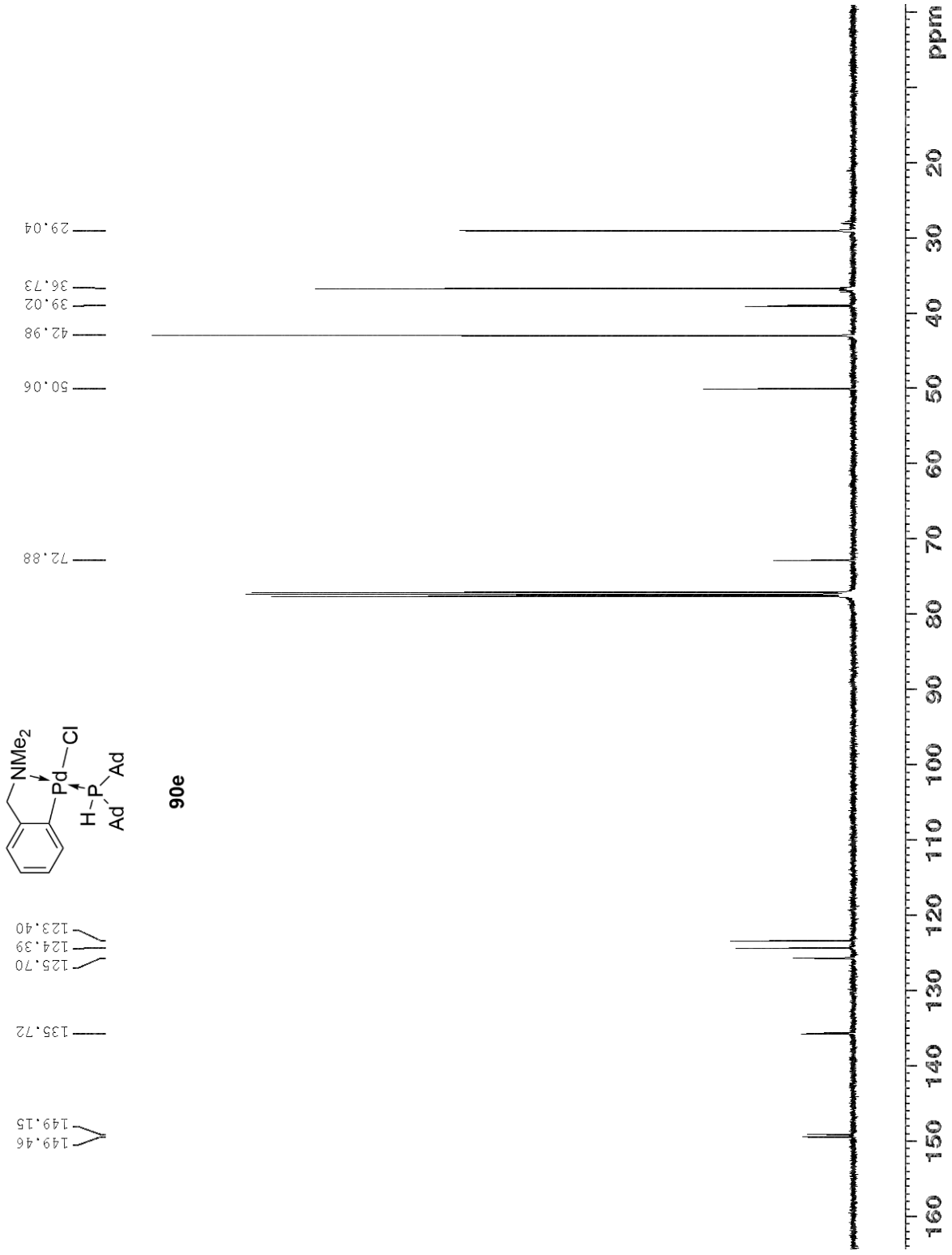


Figure 38. $^{13}C\{^{1}H\}$ NMR spectrum of mononuclear complex **90e**.

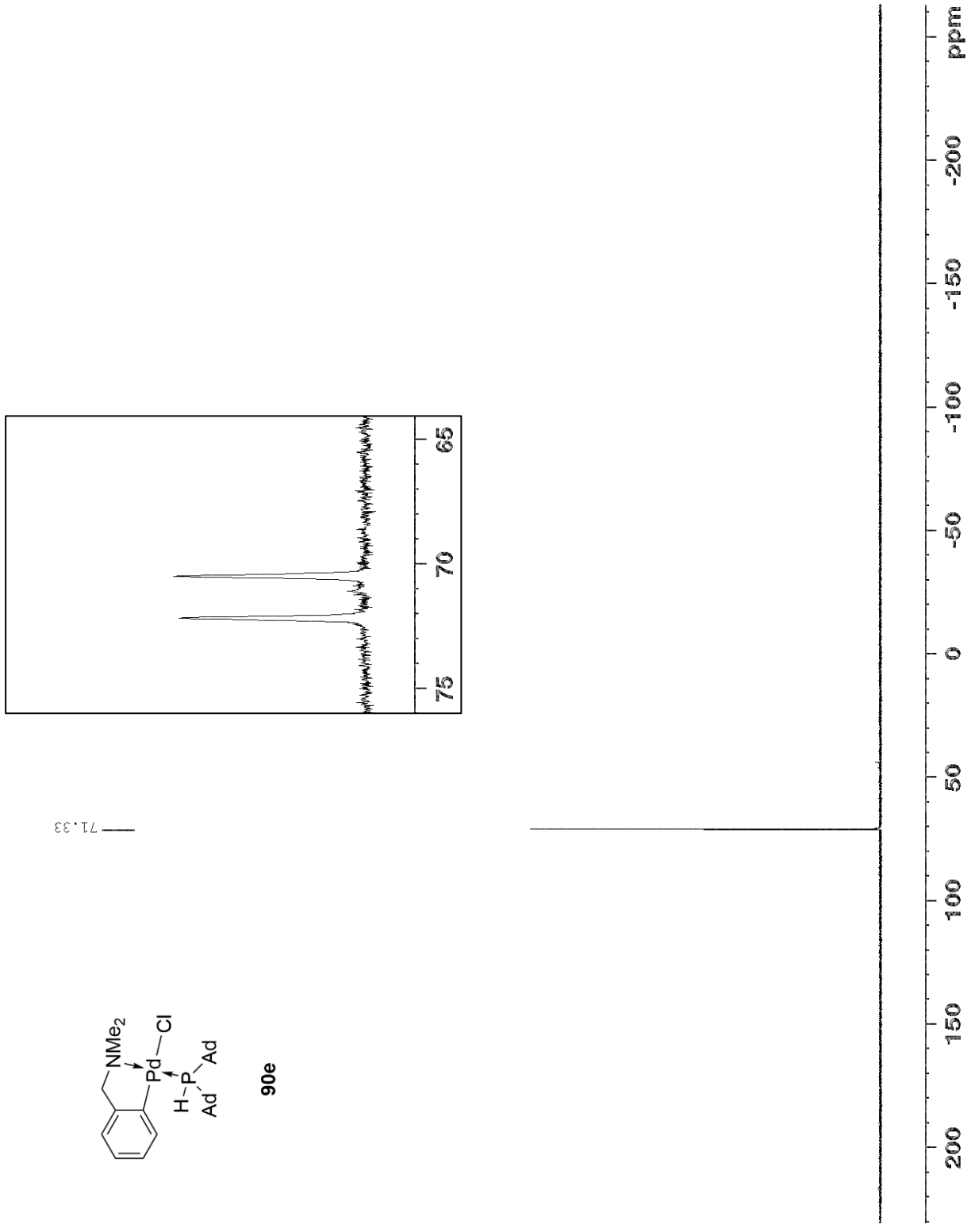


Figure 39. $^{31}P\{^{1}H\}$ NMR spectrum of mononuclear complex **90e.** (Proton-coupled ^{31}P NMR signal in expansion.)

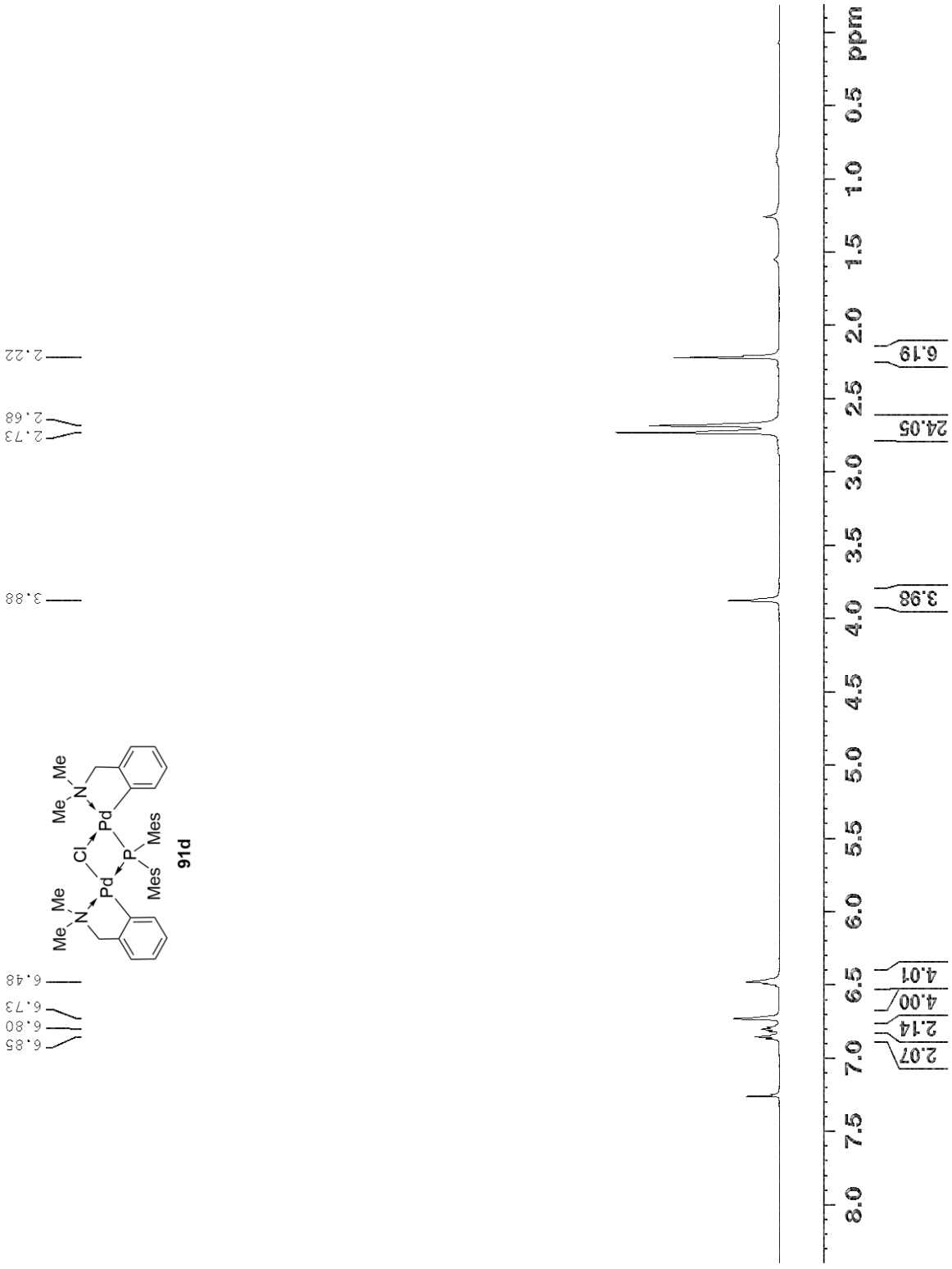


Figure 40. ^{1}H NMR spectrum of monophosphido-bridged complex **91d**.

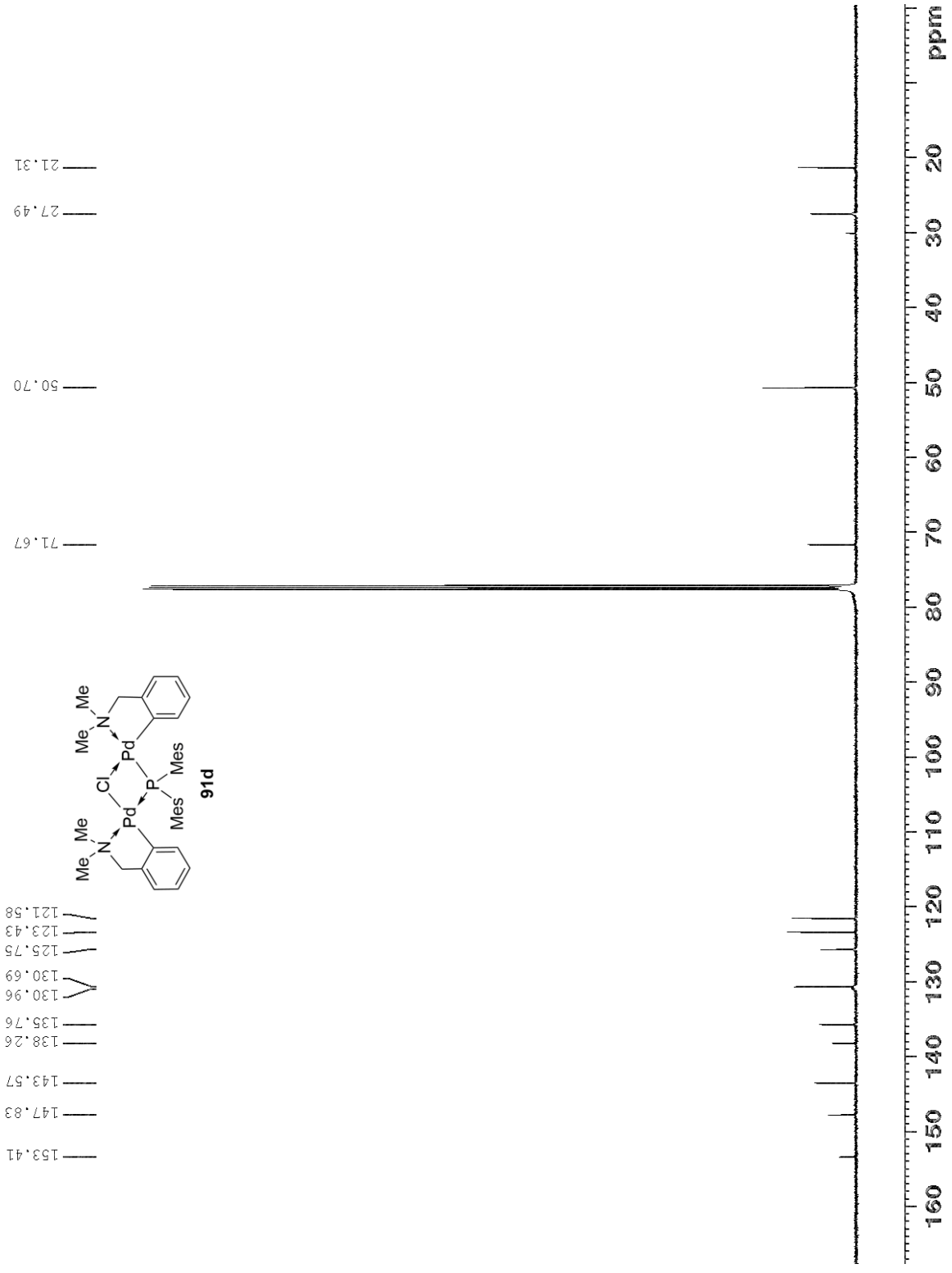


Figure 41. $^{13}C\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **91d**.

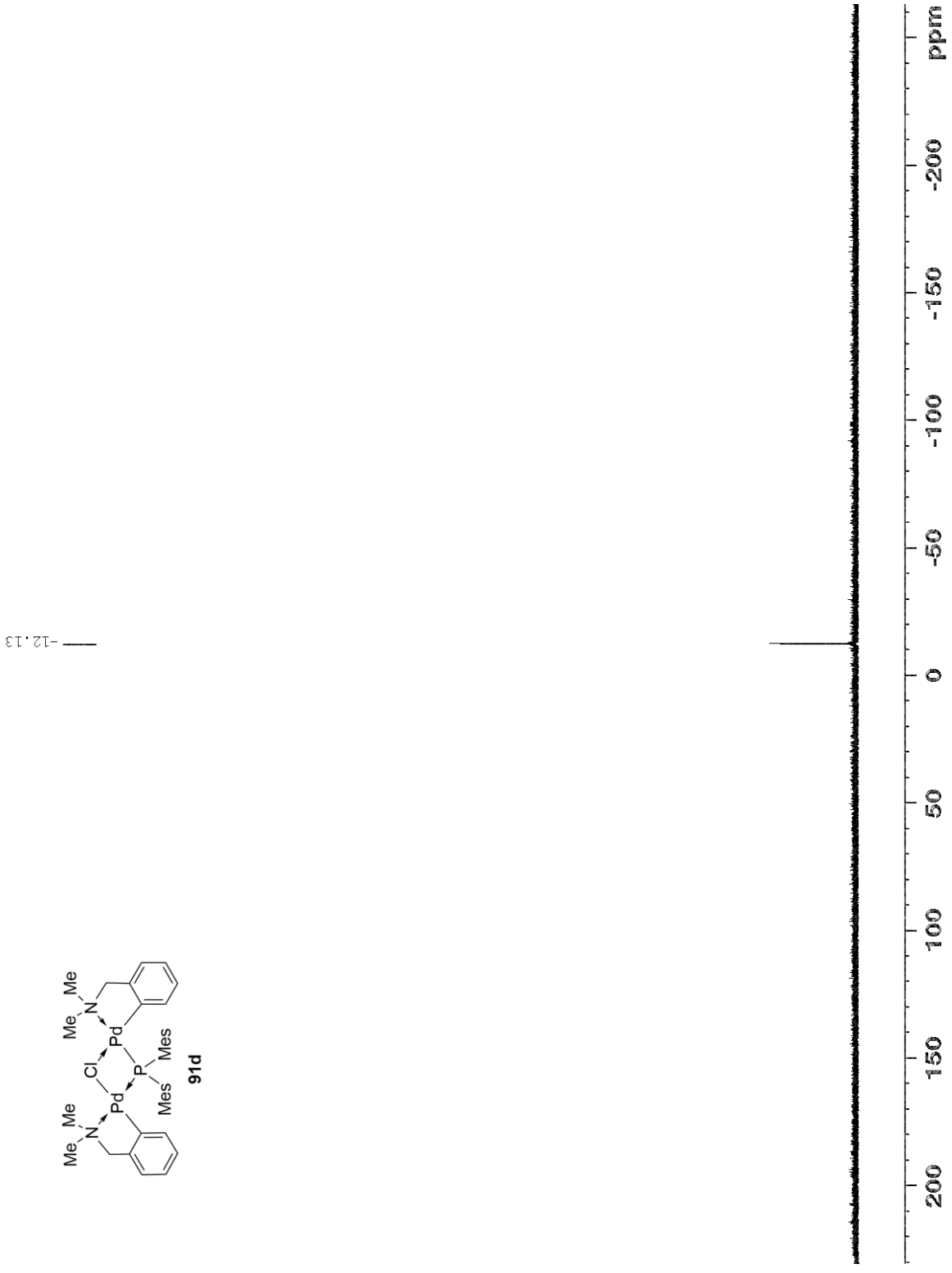


Figure 42. $^{31}P\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **91d**.

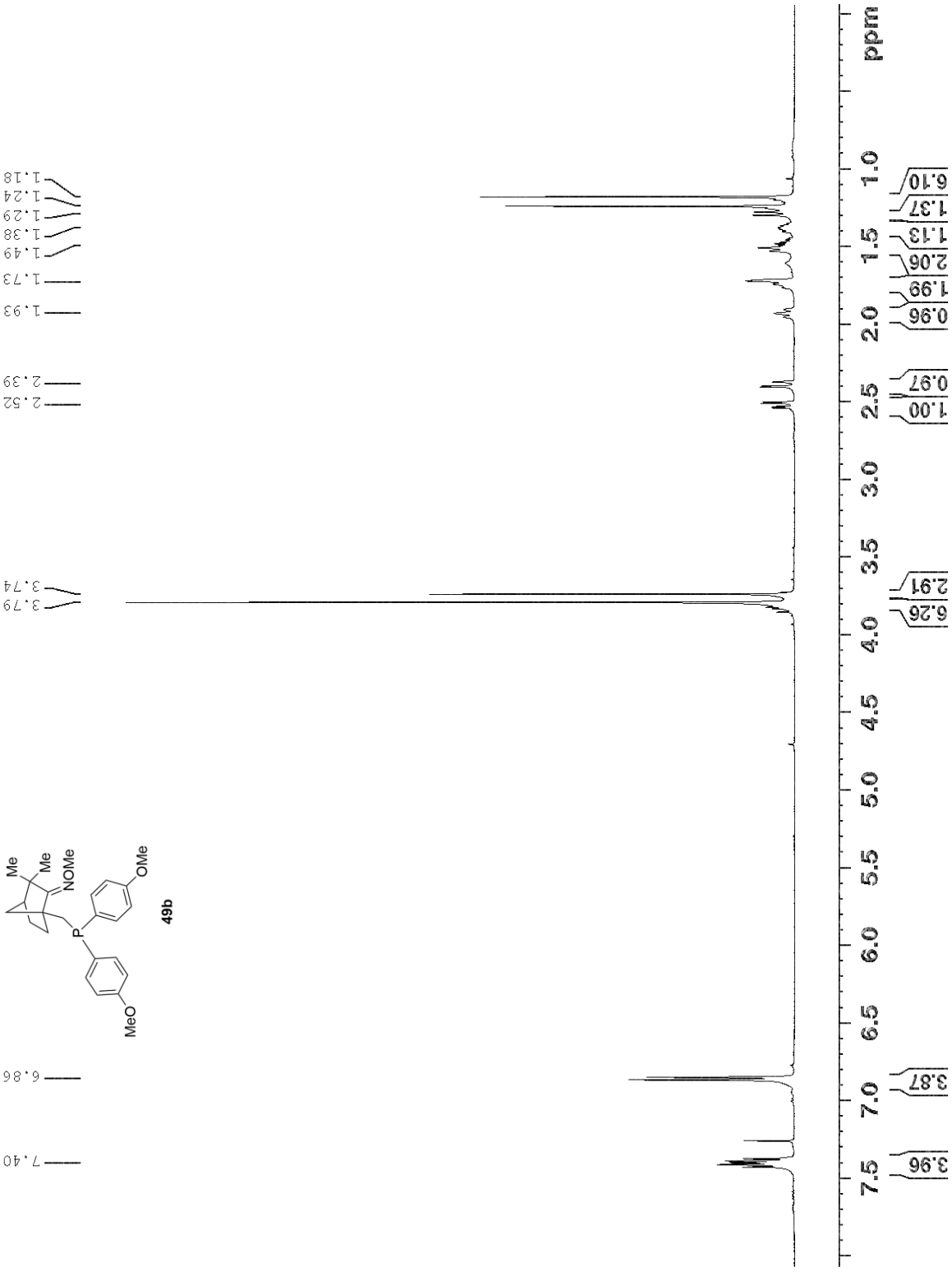


Figure 43. ^{1}H NMR spectrum of aminophosphine **49b**.

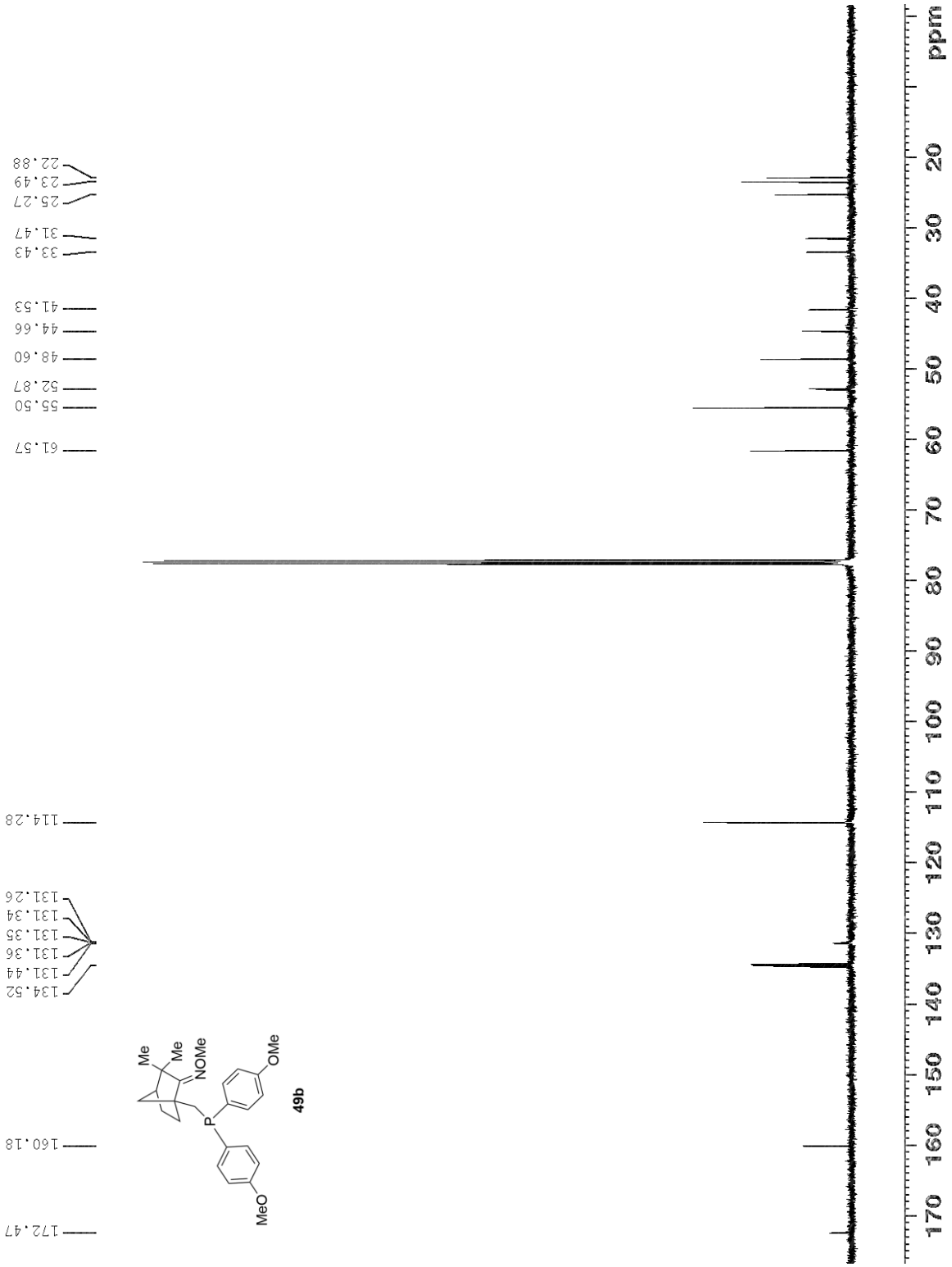


Figure 44. $^{13}C\{^{1}H\}$ NMR spectrum of aminophosphine **49b**.

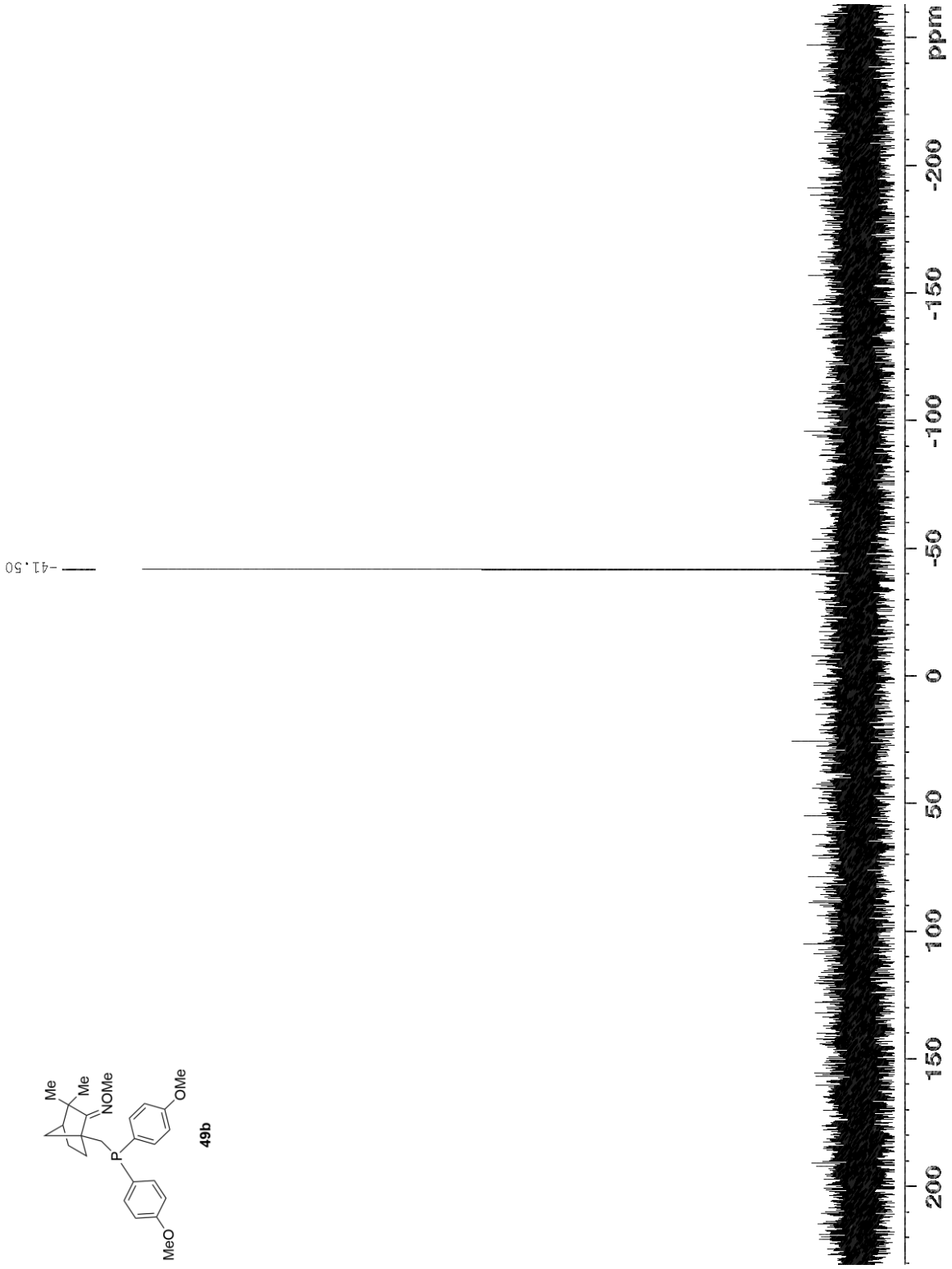


Figure 45. $^{31}P\{^{1}H\}$ NMR spectrum of aminophosphine **49b**.

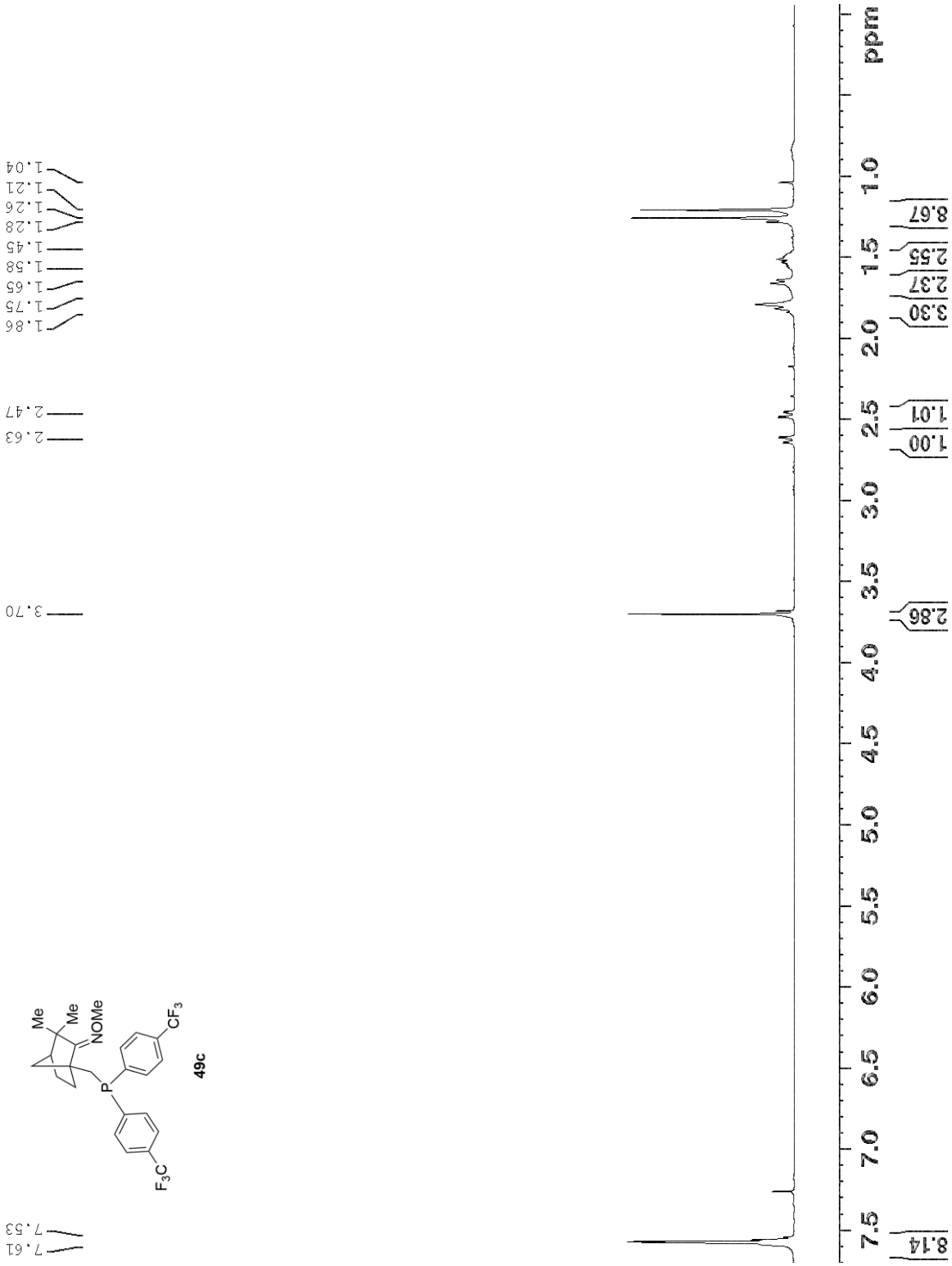


Figure 46. ^{1}H NMR spectrum of aminophosphine **49c**.

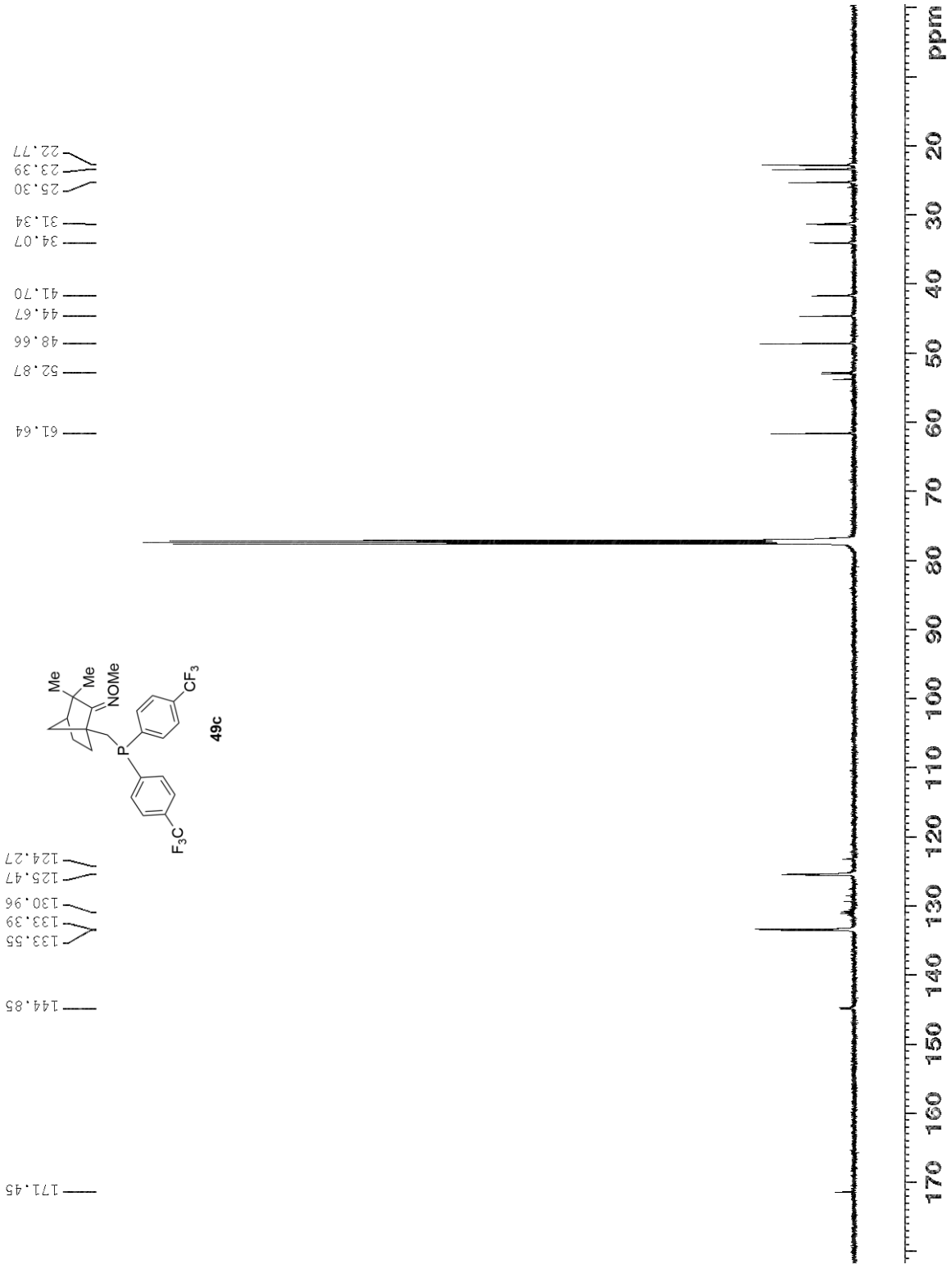


Figure 47. $^{13}C\{^{1}H\}$ NMR spectrum of aminophosphine **49c**.

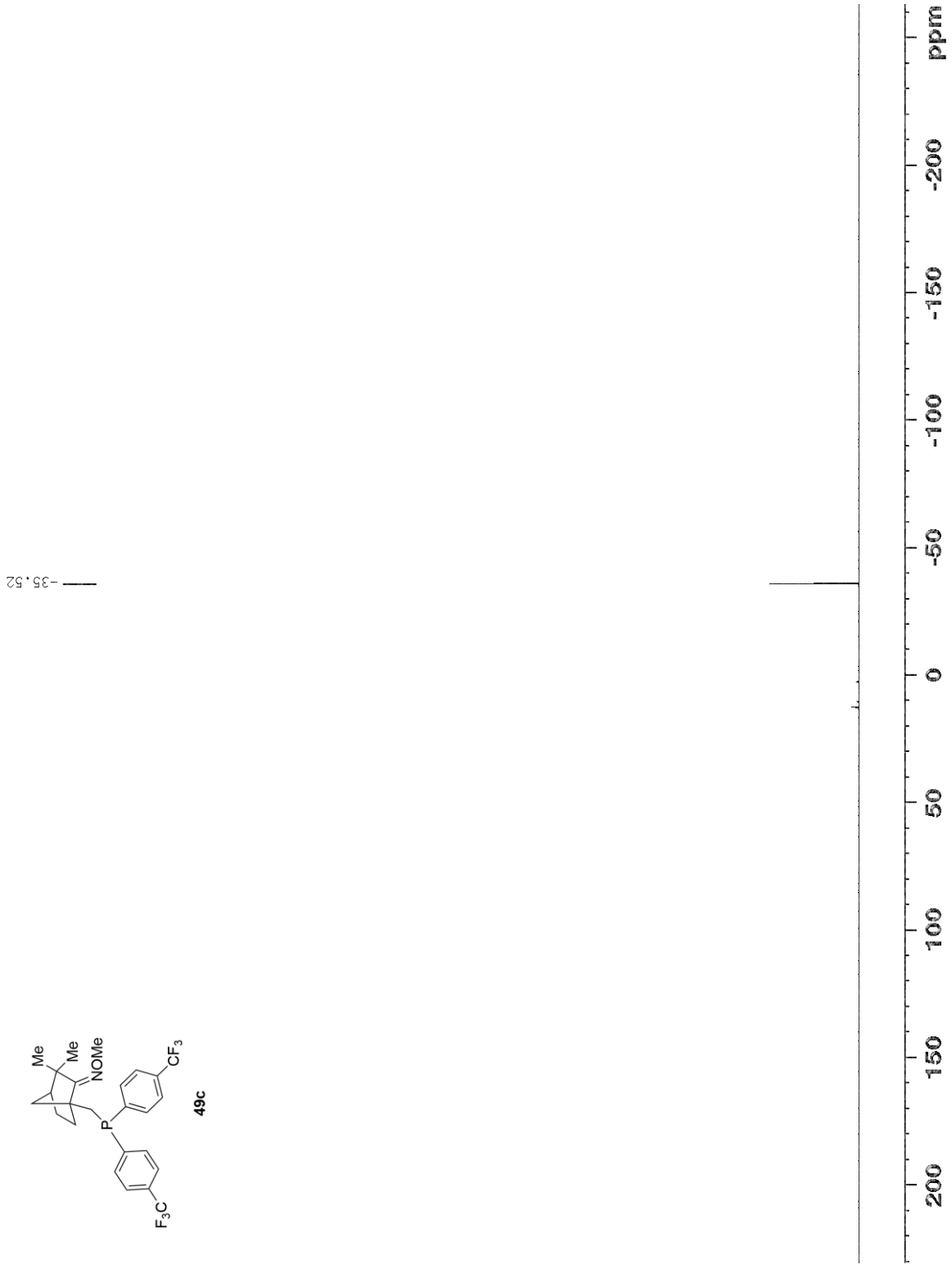


Figure 48. $^{31}P\{^{1}H\}$ NMR spectrum of aminophosphine **49c**.

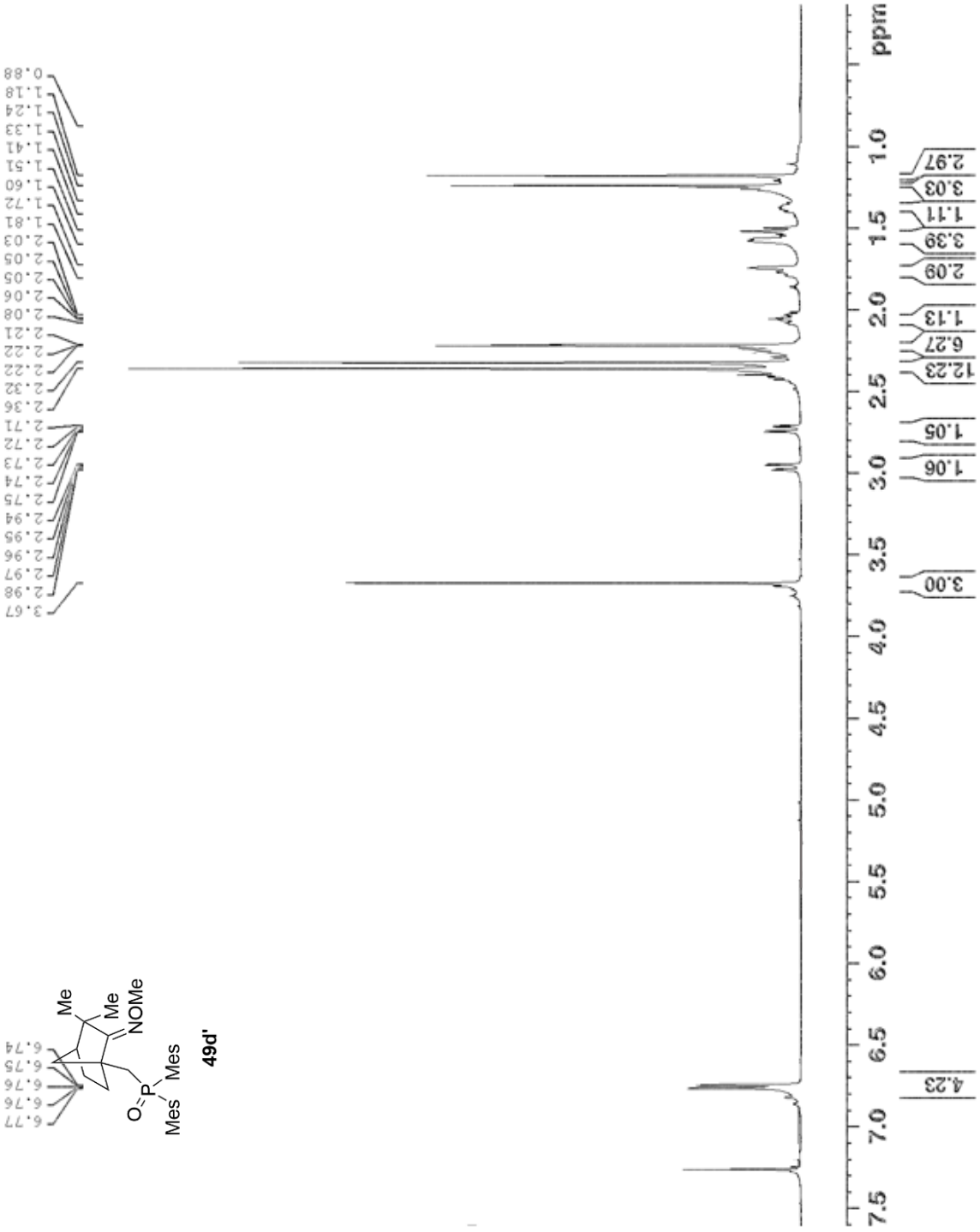


Figure 49. ^{1}H NMR spectrum of aminophosphine oxide **49d'**.

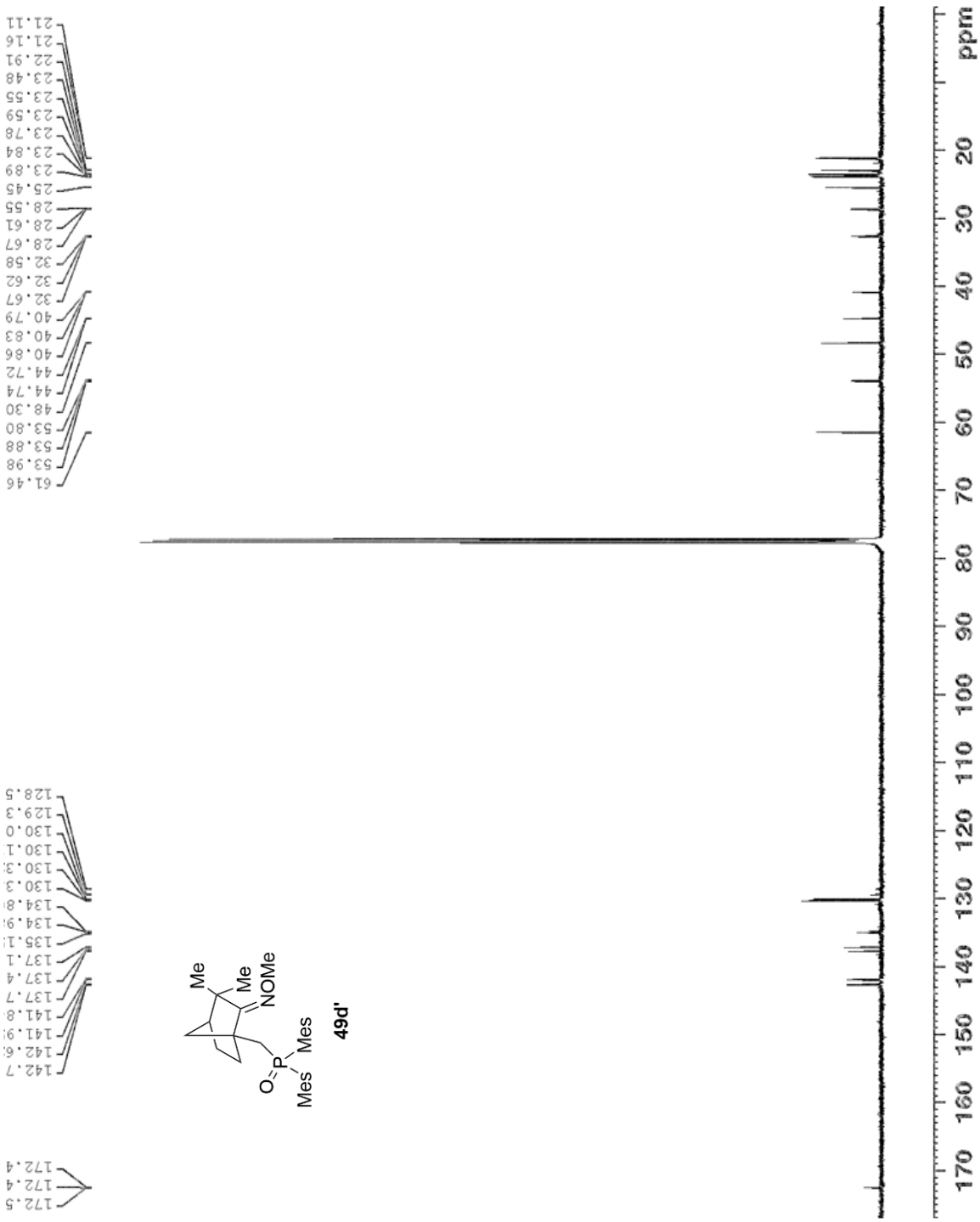


Figure 50. $^{13}C\{^{1}H\}$ NMR spectrum of aminophosphine oxide **49d'**.

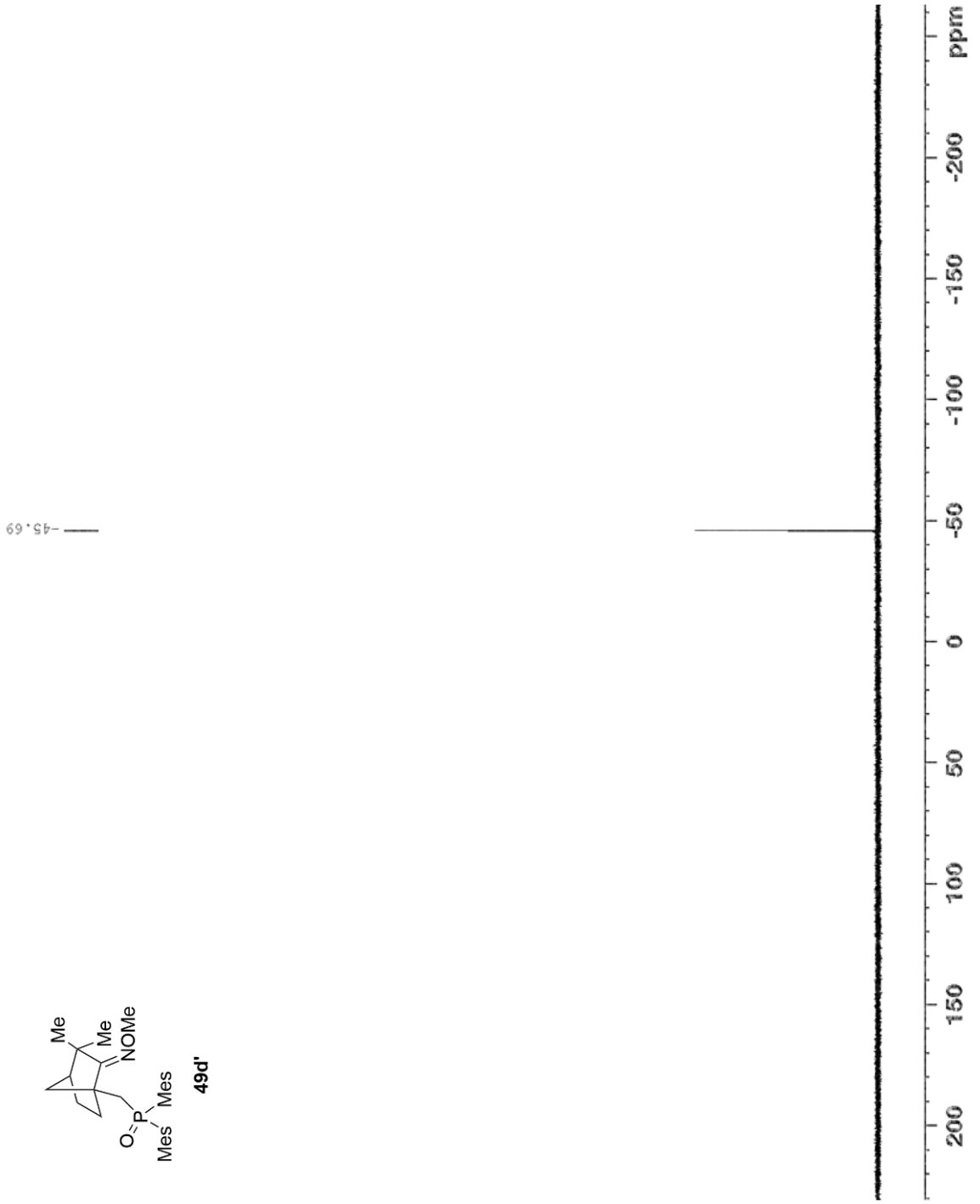


Figure 51. $^{31}P\{^{1}H\}$ NMR spectrum of aminophosphine **49d'**.

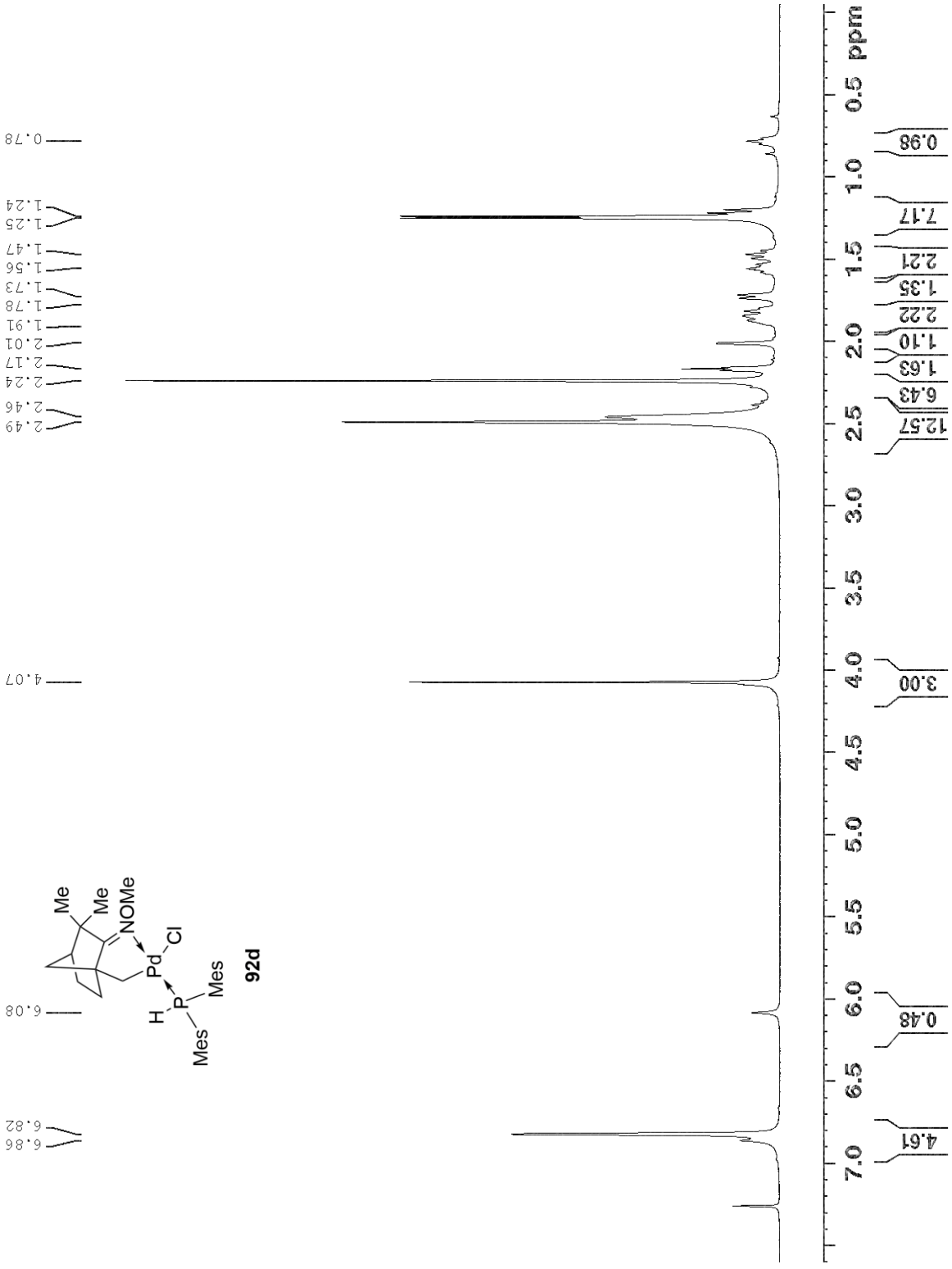


Figure 52. ^{1}H NMR spectrum of complex **92d**.

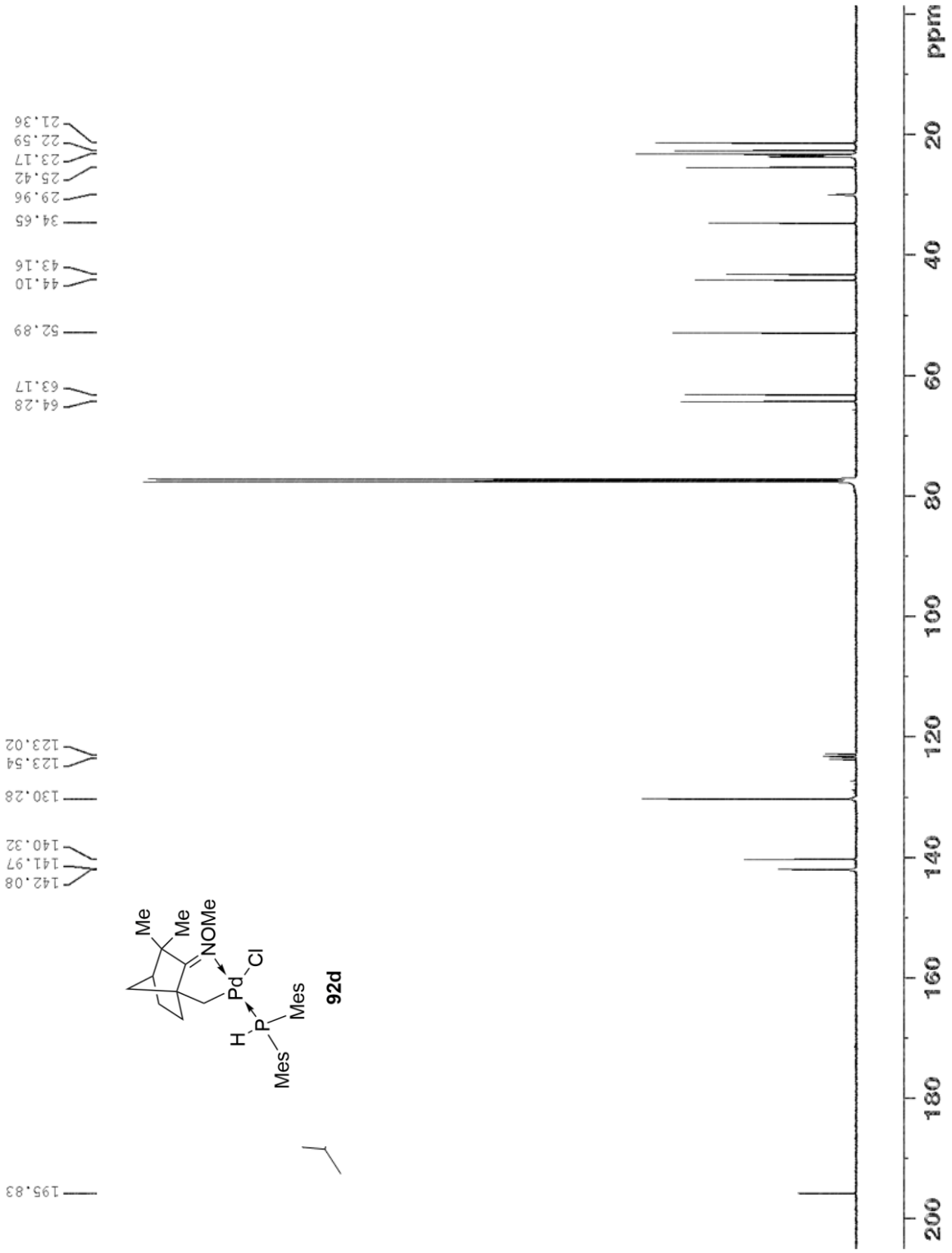


Figure 53. $^{13}C\{^{1}H\}$ NMR spectrum of complex **92d**.

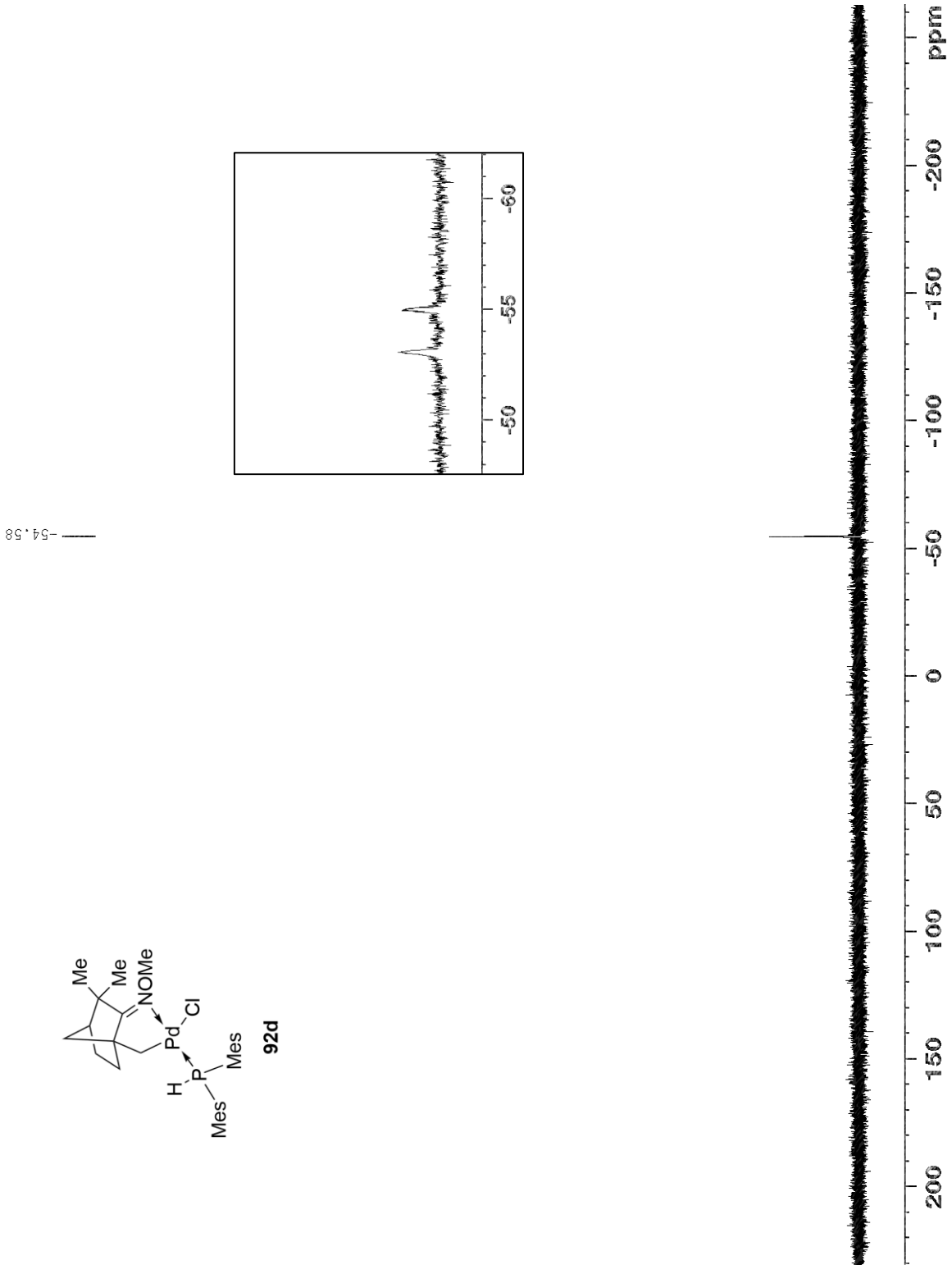


Figure 54. $^{31}P\{^{1}H\}$ NMR spectrum of mononuclear complex **92d.** (Proton-coupled ^{31}P NMR signal in expansion.)

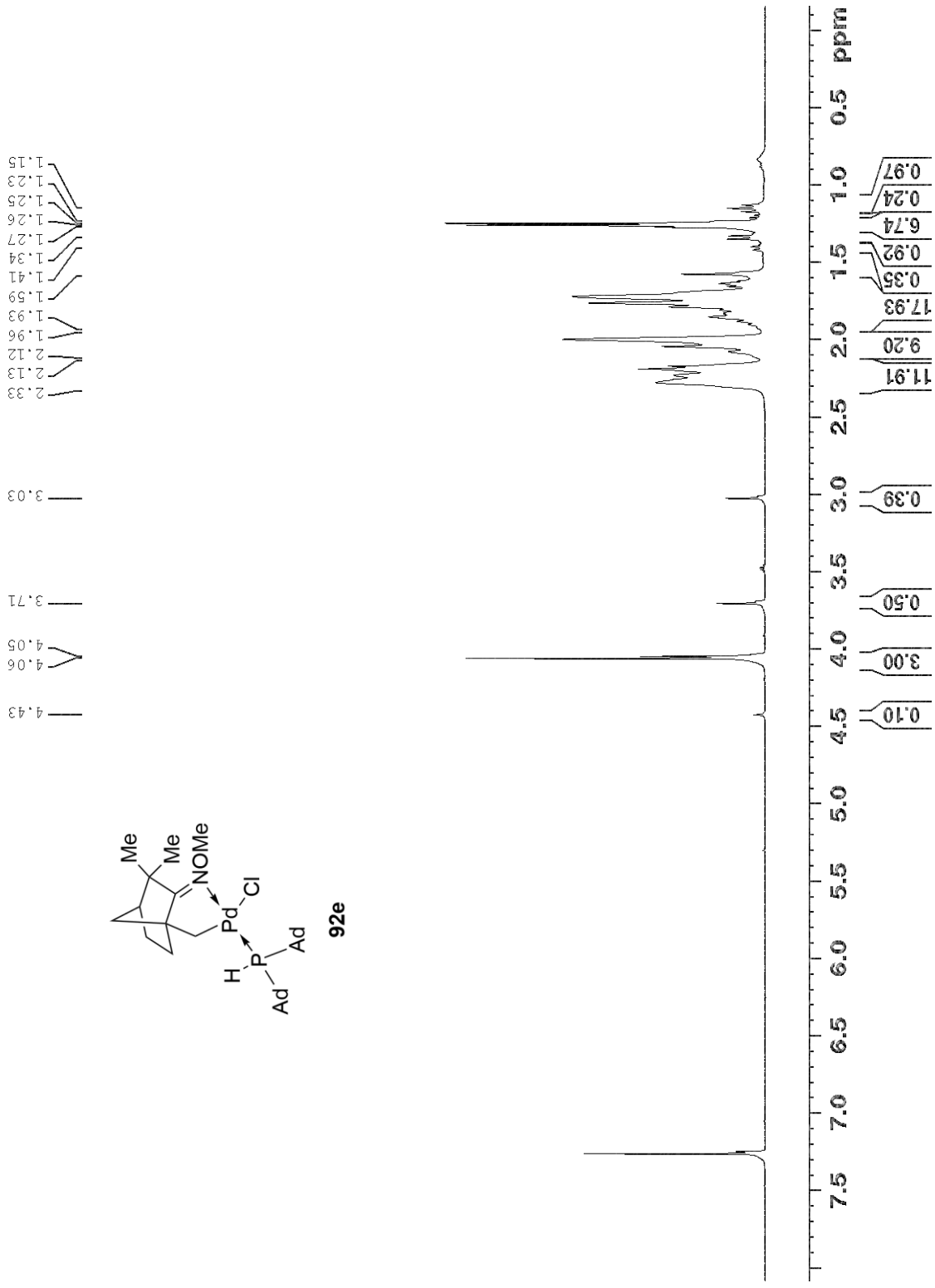


Figure 55. ^{1}H NMR spectrum of mononuclear complex **92e**.

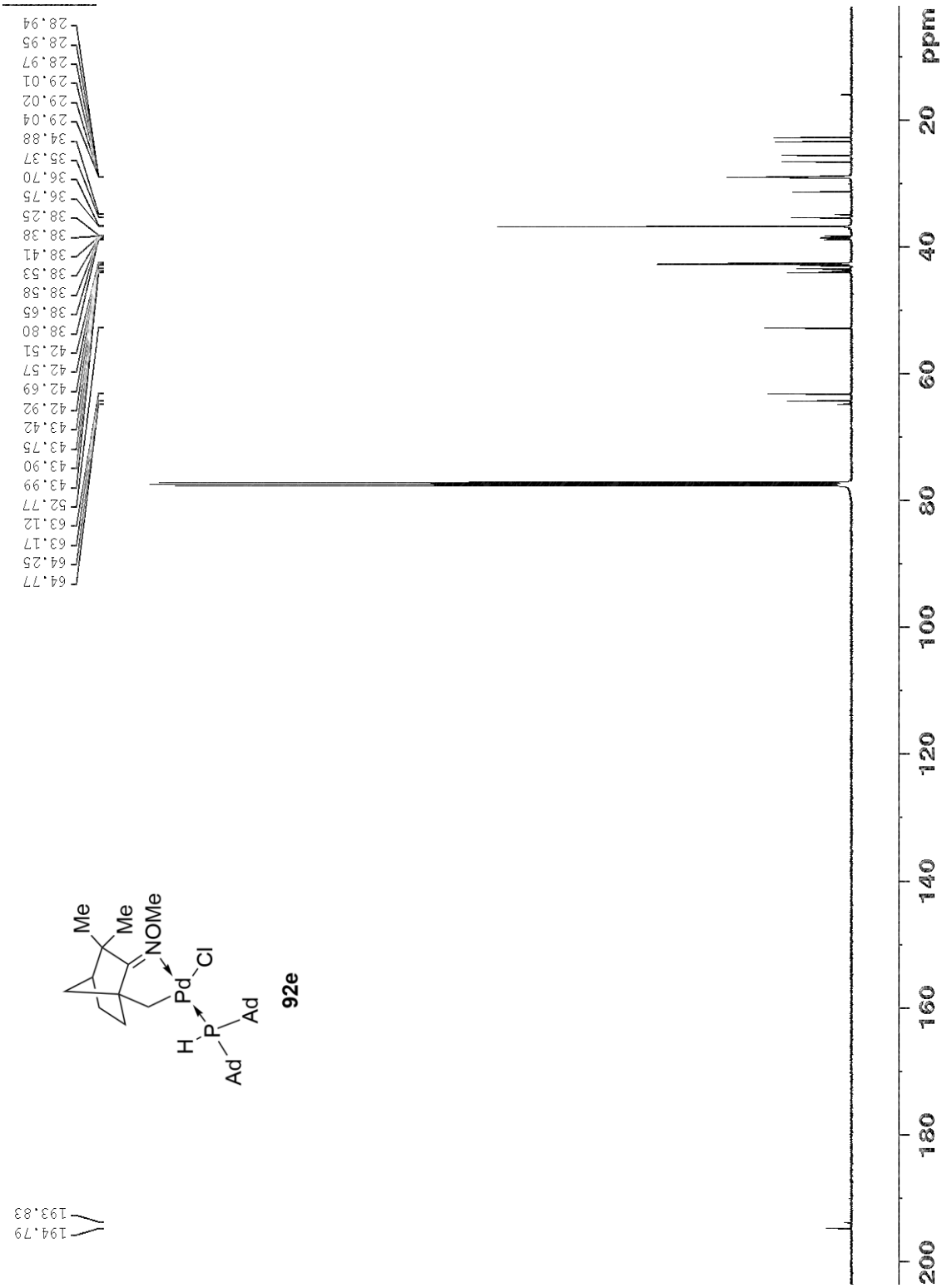


Figure 56. $^{13}C\{^{1}H\}$ NMR spectrum of mononuclear complex **92e.**

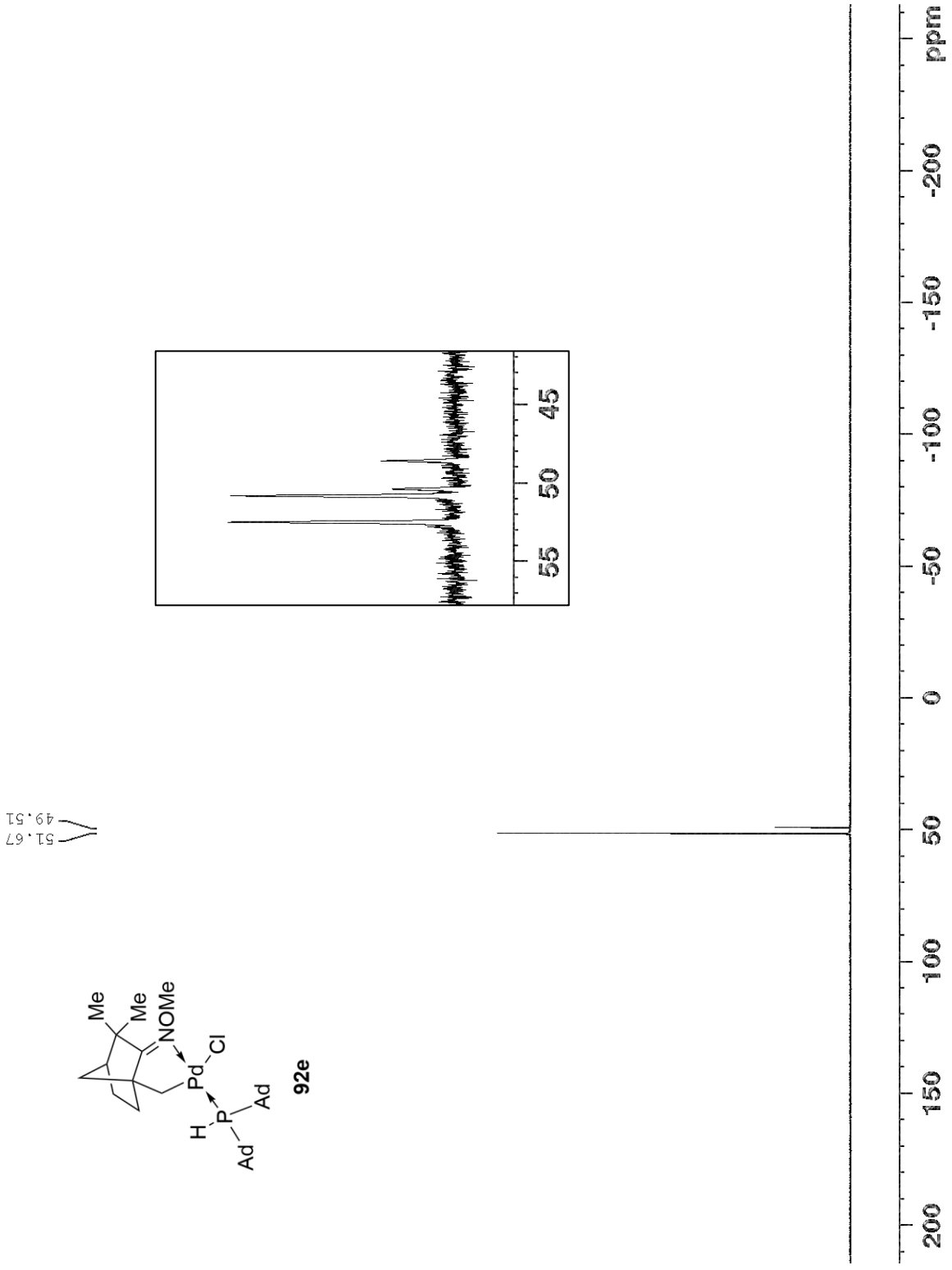


Figure 57. $^{31}P\{^{1}H\}$ NMR spectrum of mononuclear complex **92e.** (Proton-coupled ^{31}P NMR signal in expansion.)

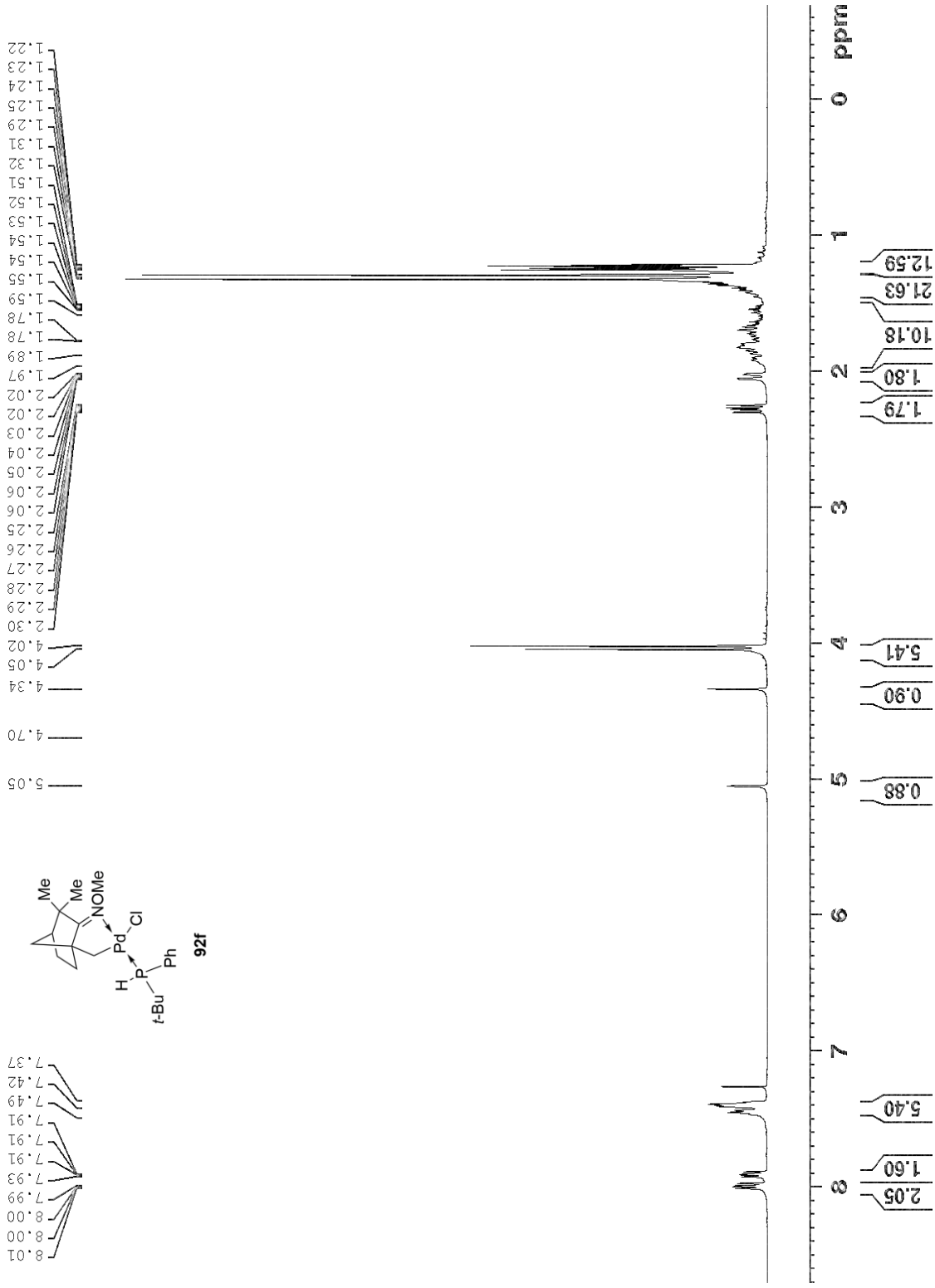


Figure 58. ^{1}H NMR spectrum of mononuclear complex **92f.**

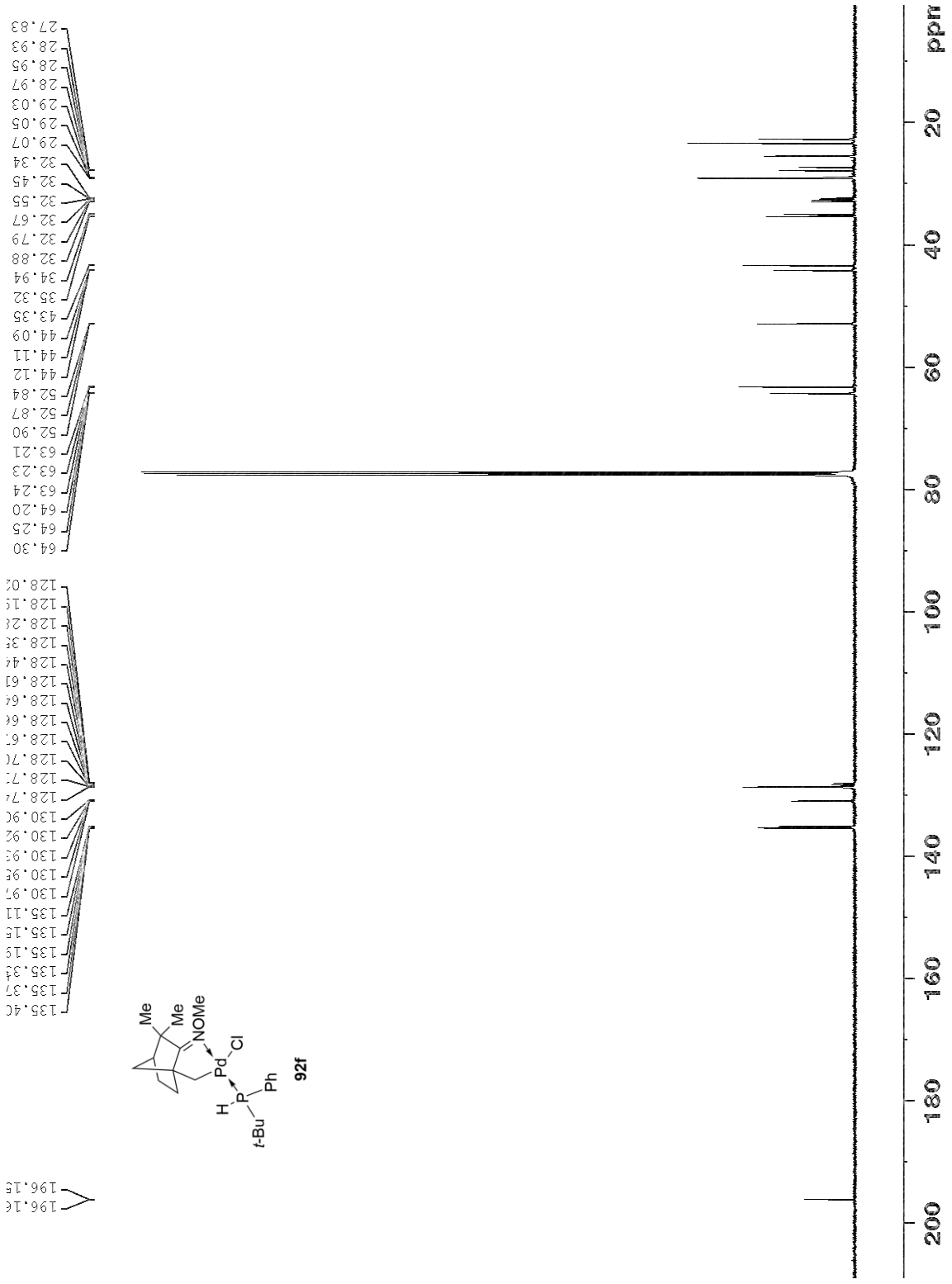


Figure 59. $^{13}C\{^{1}H\}$ NMR spectrum of mononuclear complex **92f.**

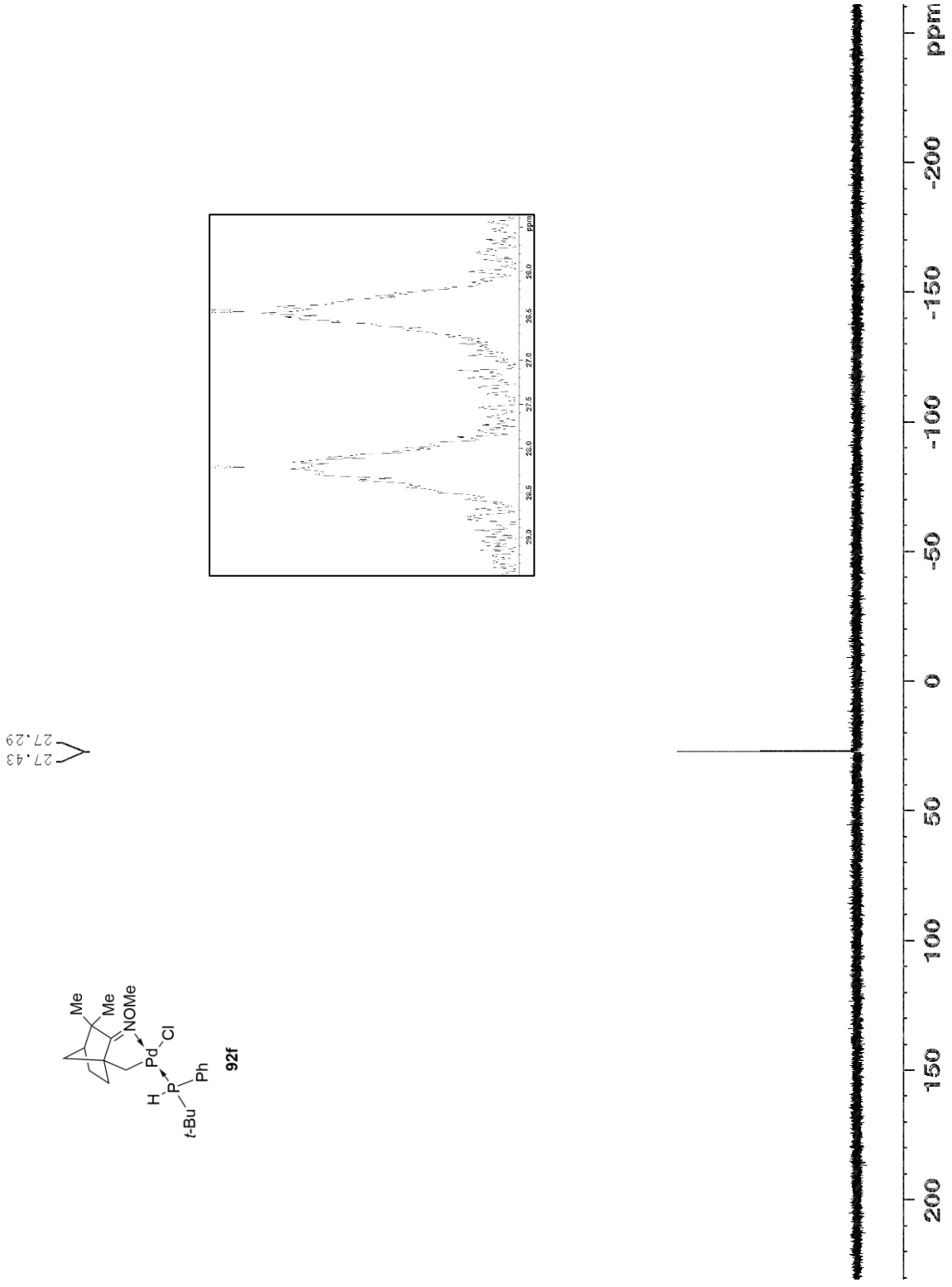


Figure 60. $^{31}P\{^{1}H\}$ NMR spectrum of mononuclear complex **92f.** (Proton-coupled ^{31}P NMR signal in expansion.)

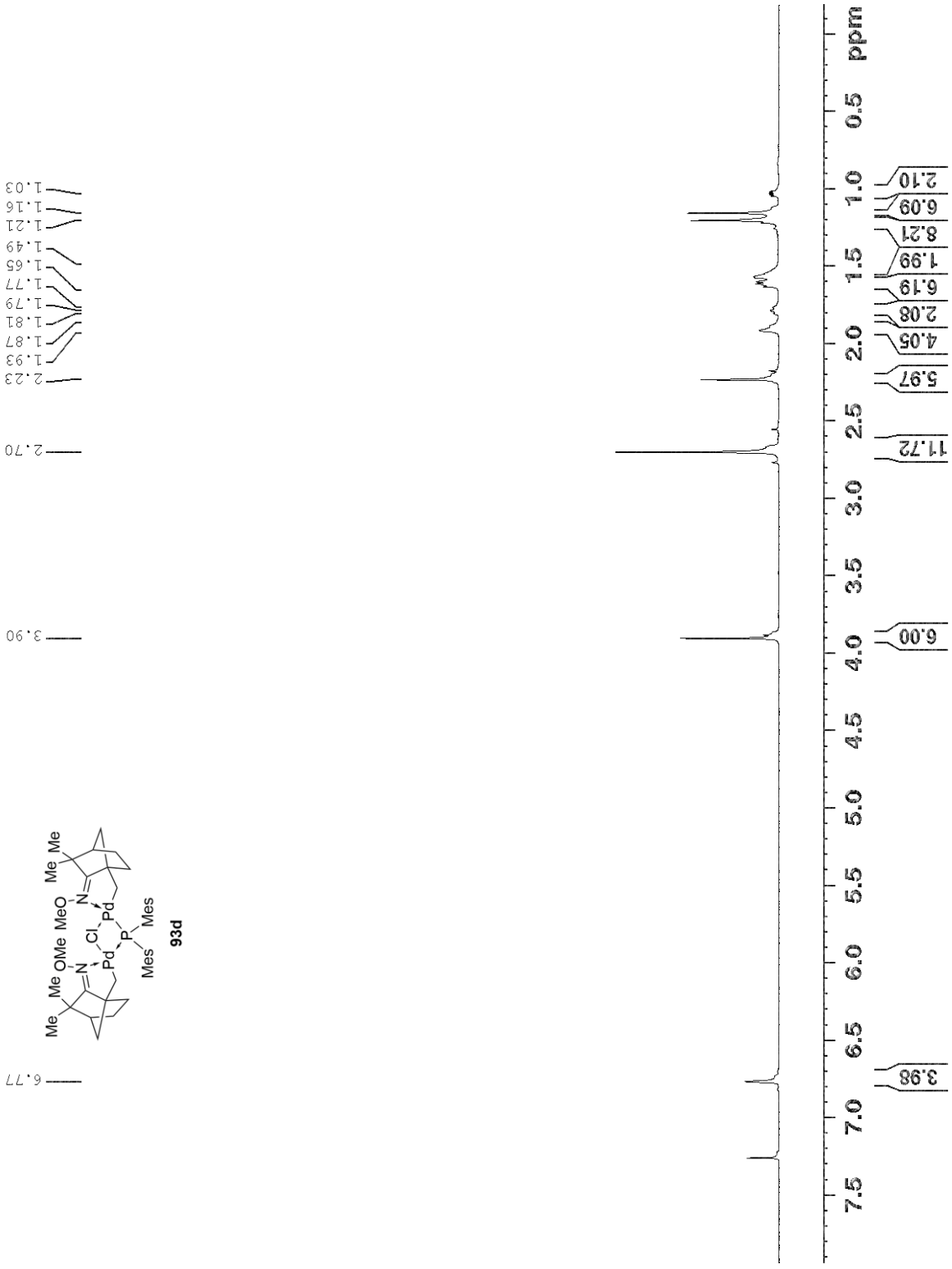


Figure 61. ^{1}H NMR of monophosphido-bridged complex **93d**.

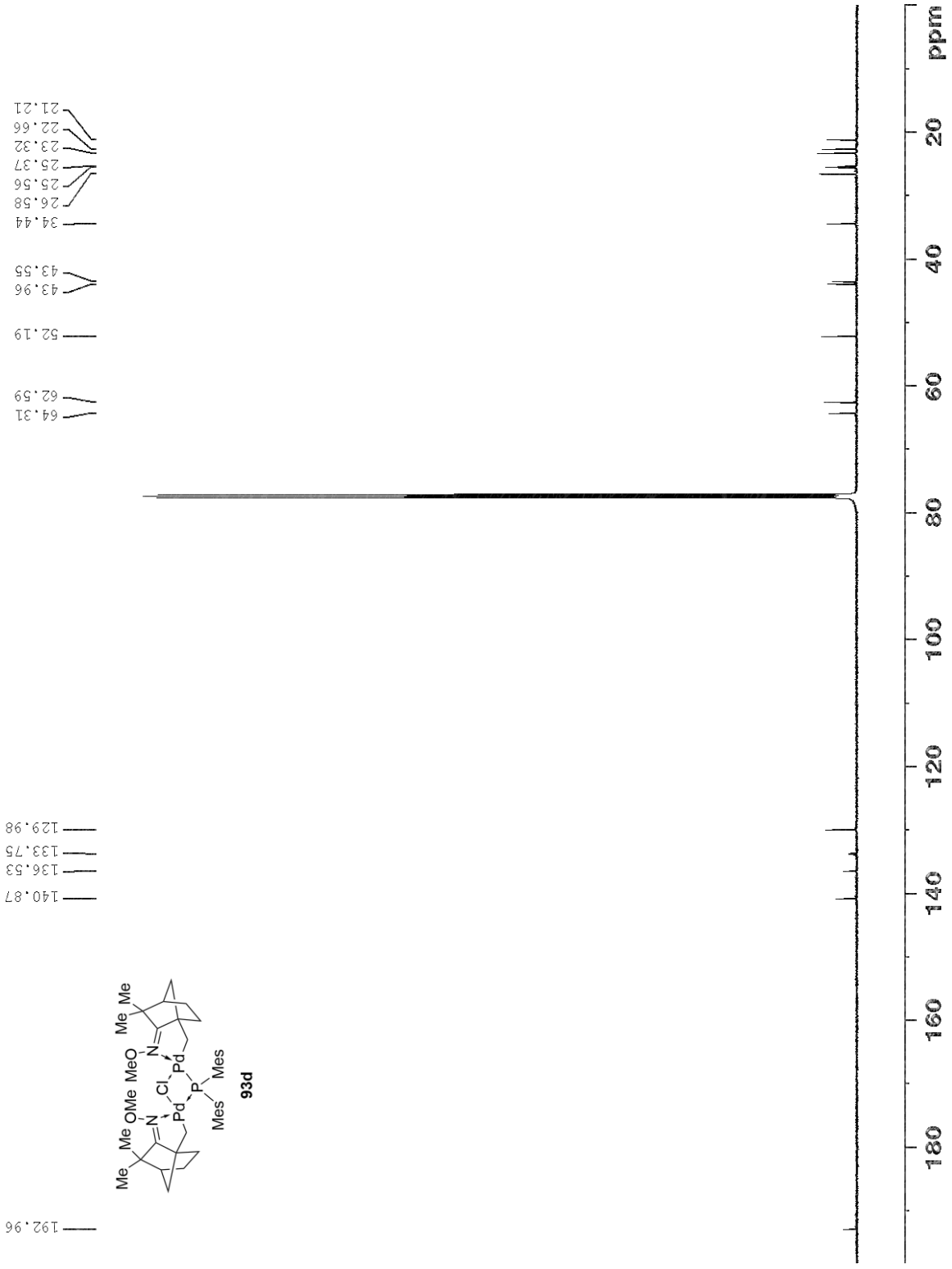


Figure 62. $^{13}C\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **93d**.

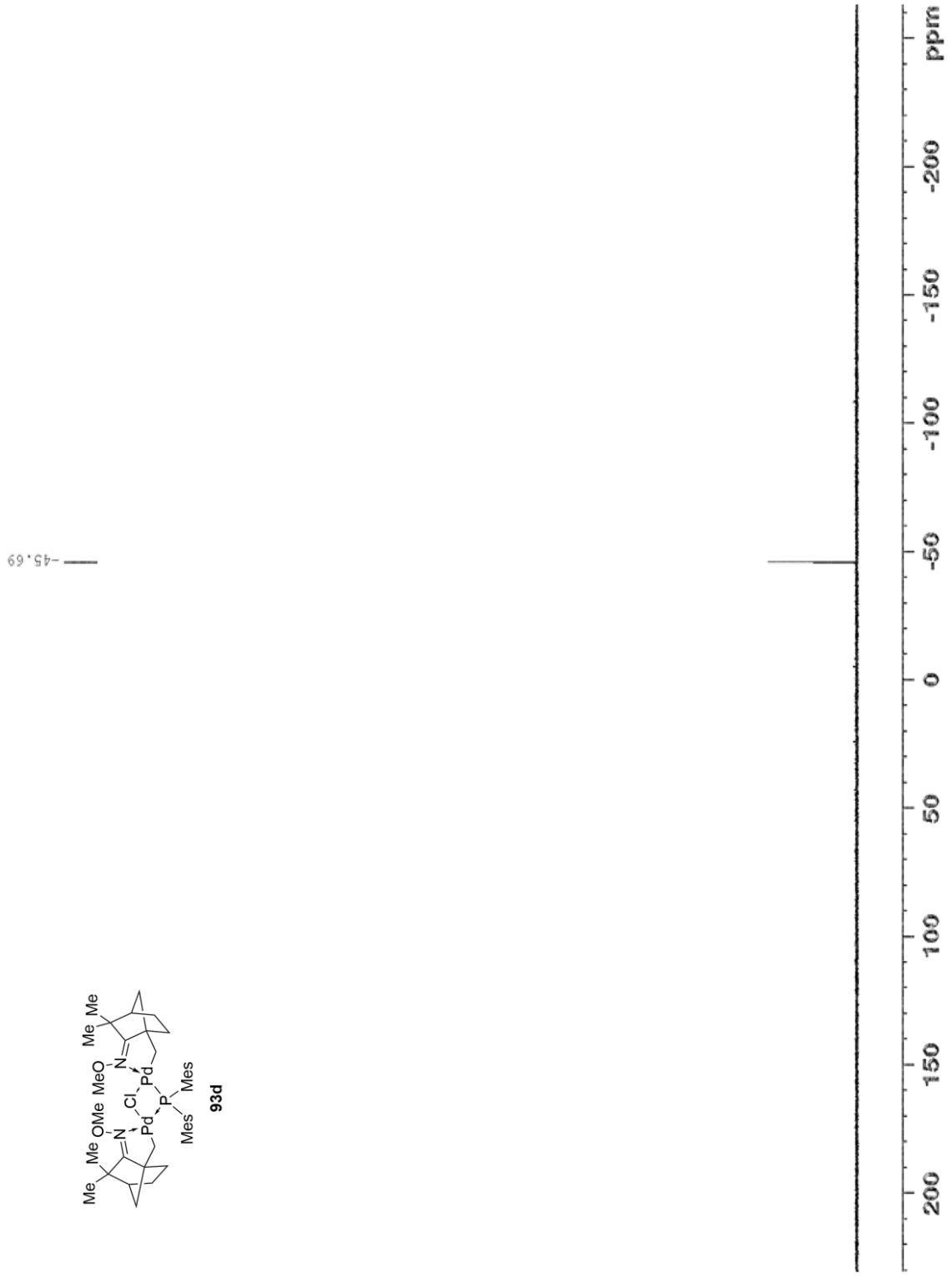


Figure 63. $^{31}P\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **93d**.

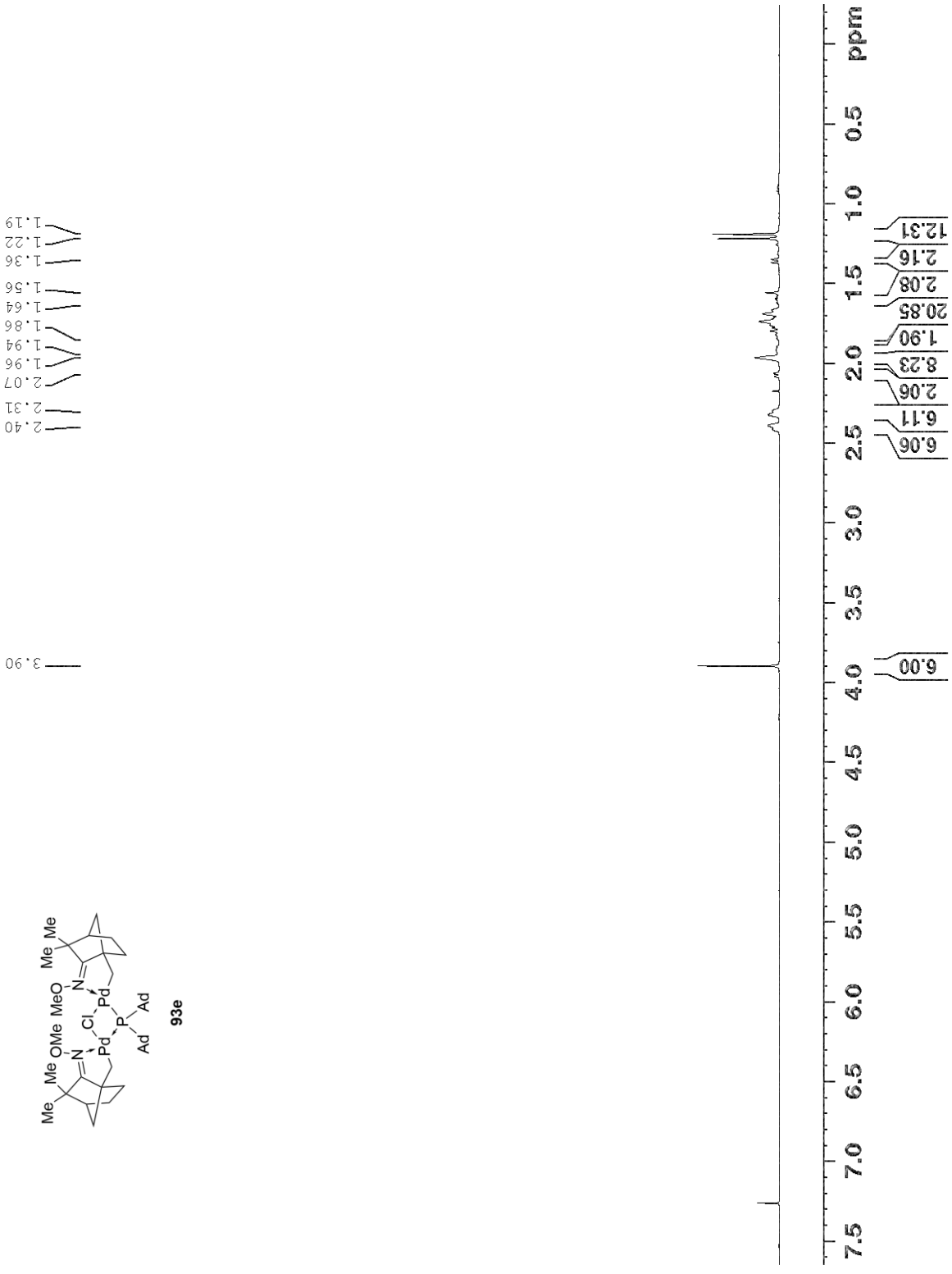


Figure 64. ^{1}H NMR spectrum of monophosphido-bridged complex **93e**.

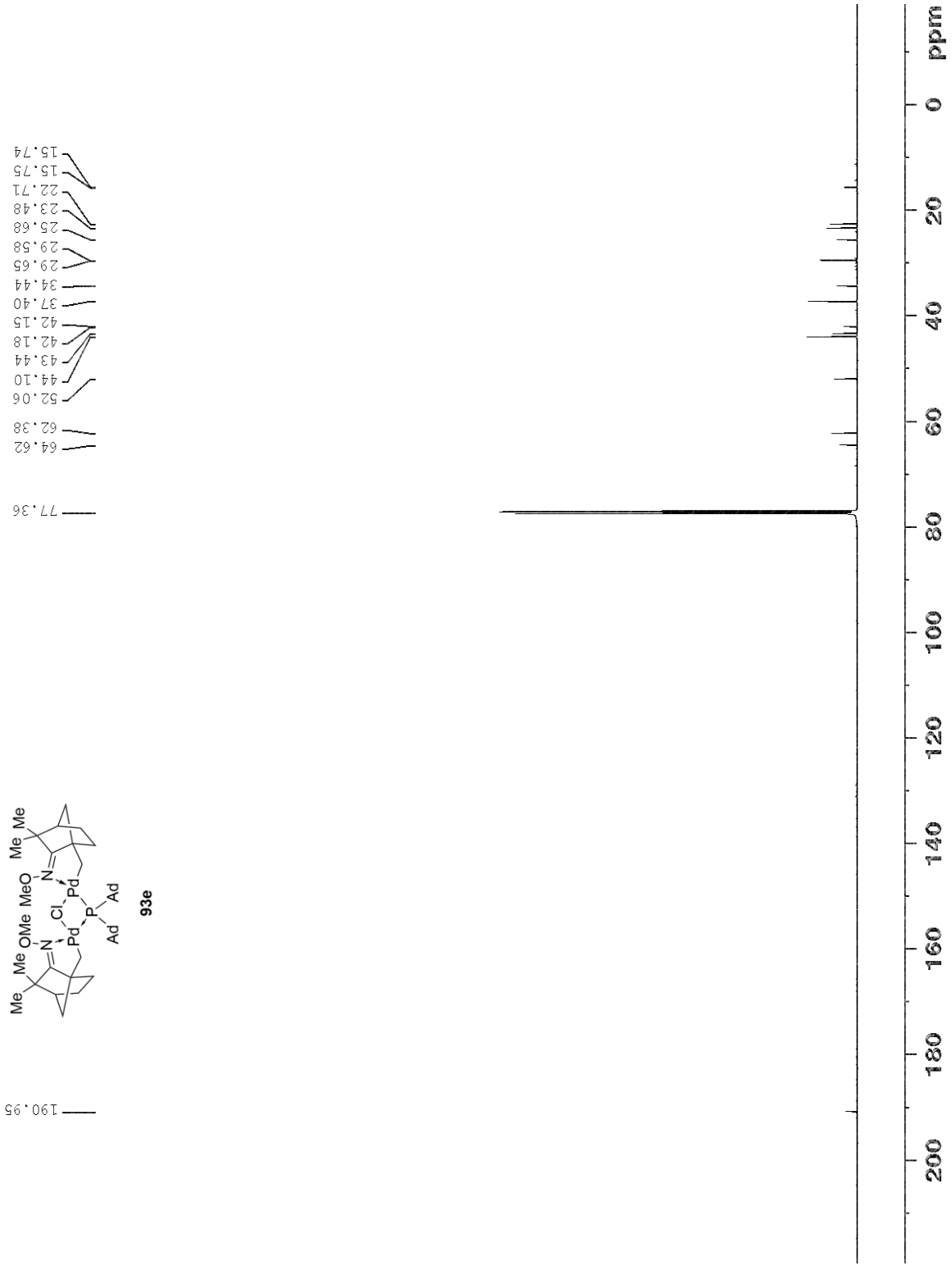


Figure 65. $^{13}C\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **93e**.

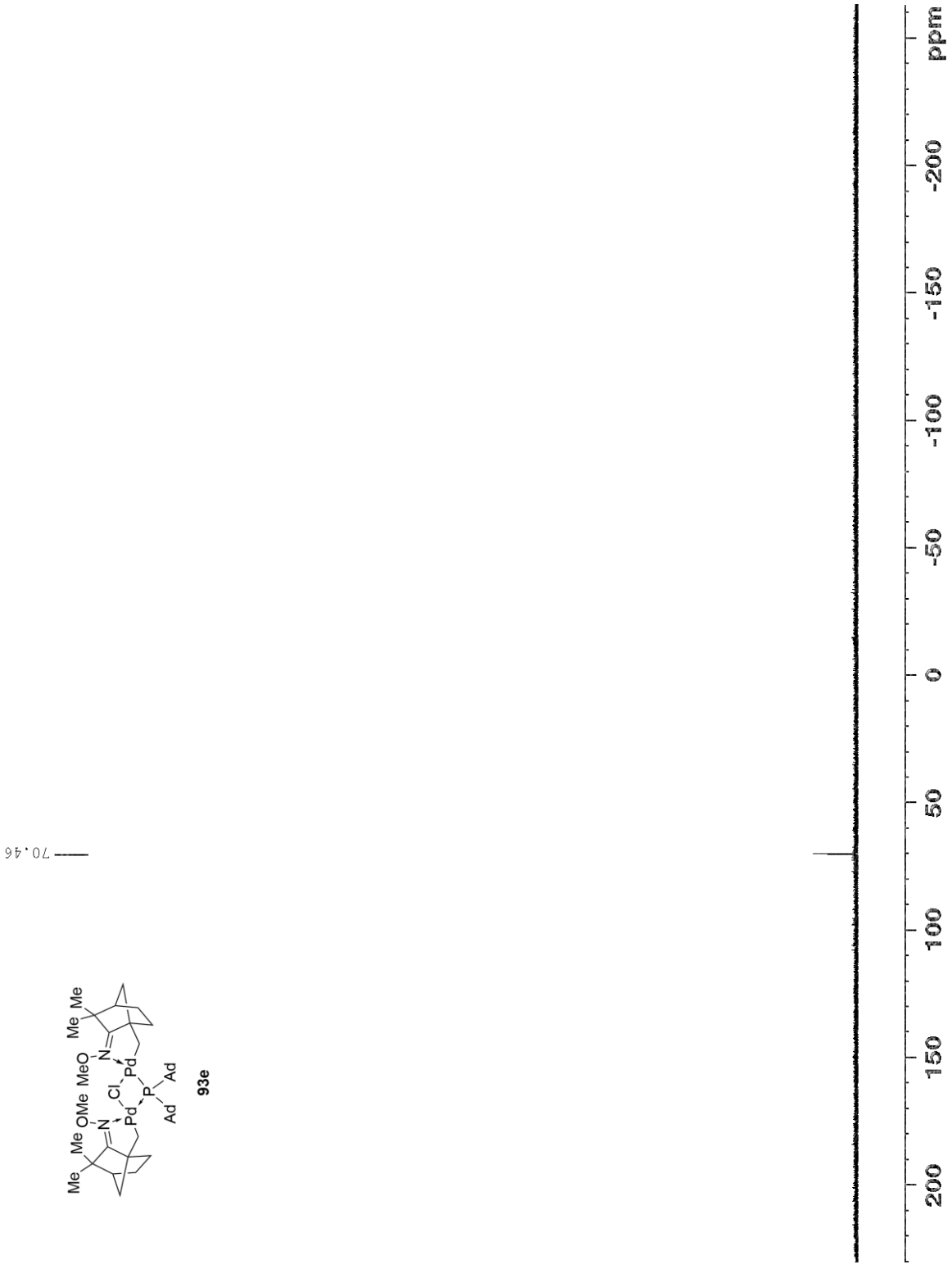


Figure 66. $^{31}P\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **93e**.

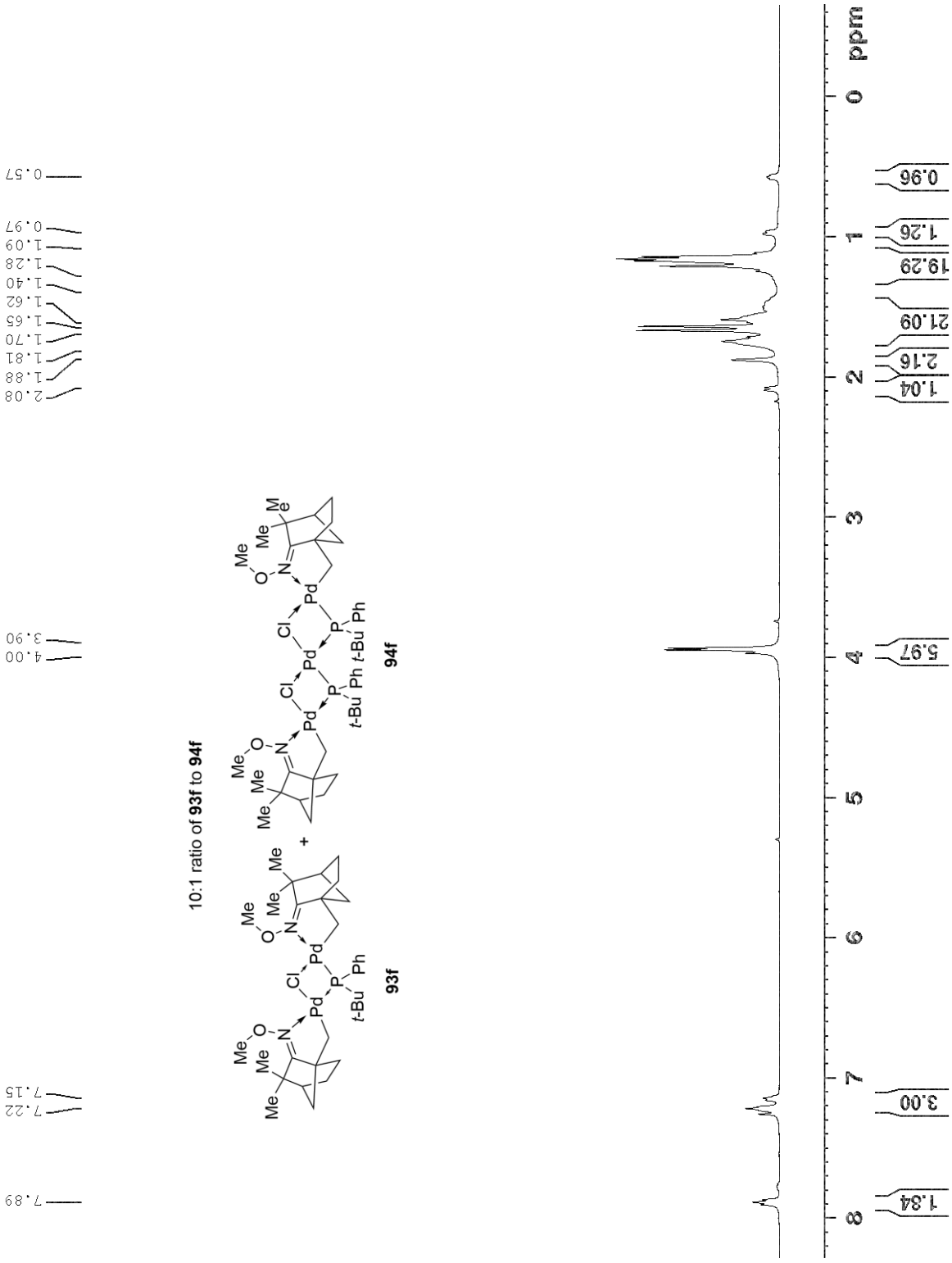


Figure 67. ^{1}H NMR spectrum of 10:1 mixture of monophosphido-bridged complex **93f** trinuclear complex **94f**.

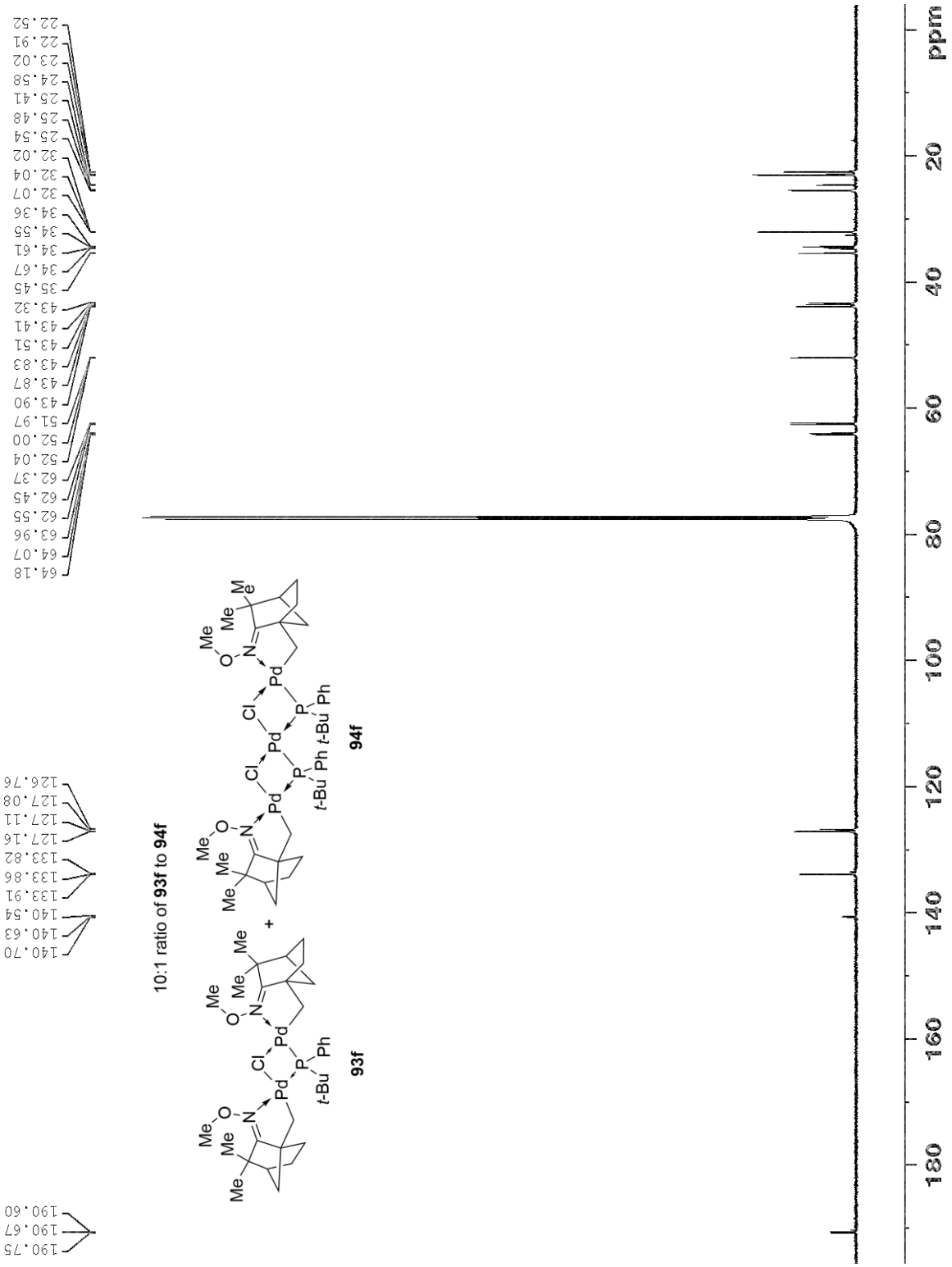


Figure 68. $^{13}C\{^{1}H\}$ NMR spectrum of 10:1 mixture of monophosphido-bridged complex **93f** trinuclear complex **94f**.

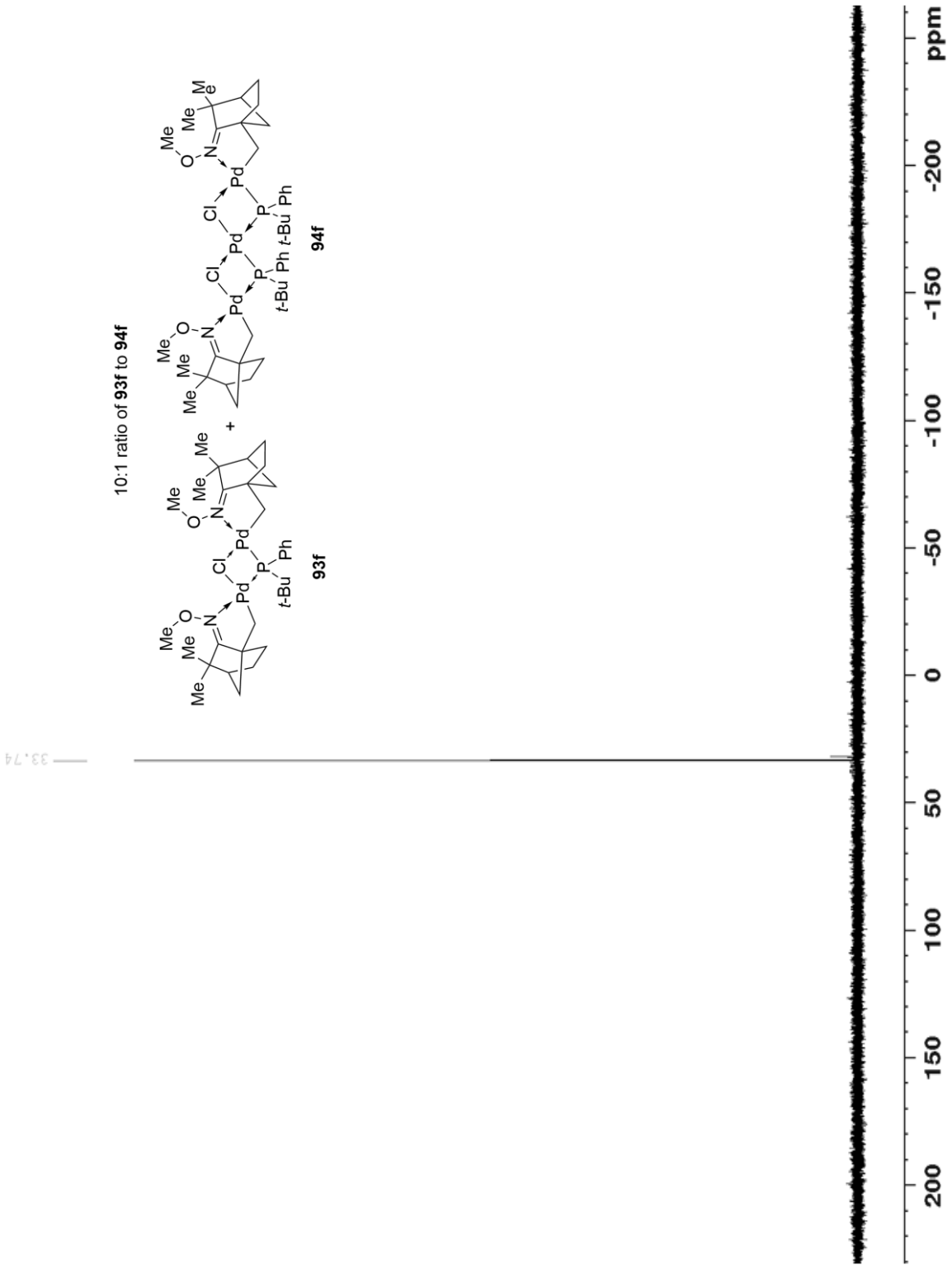


Figure 69. $^{31}P\{^{1}H\}$ NMR spectrum of 10:1 mixture of monophosphido-bridged complex **93f** trinuclear complex **94f**.

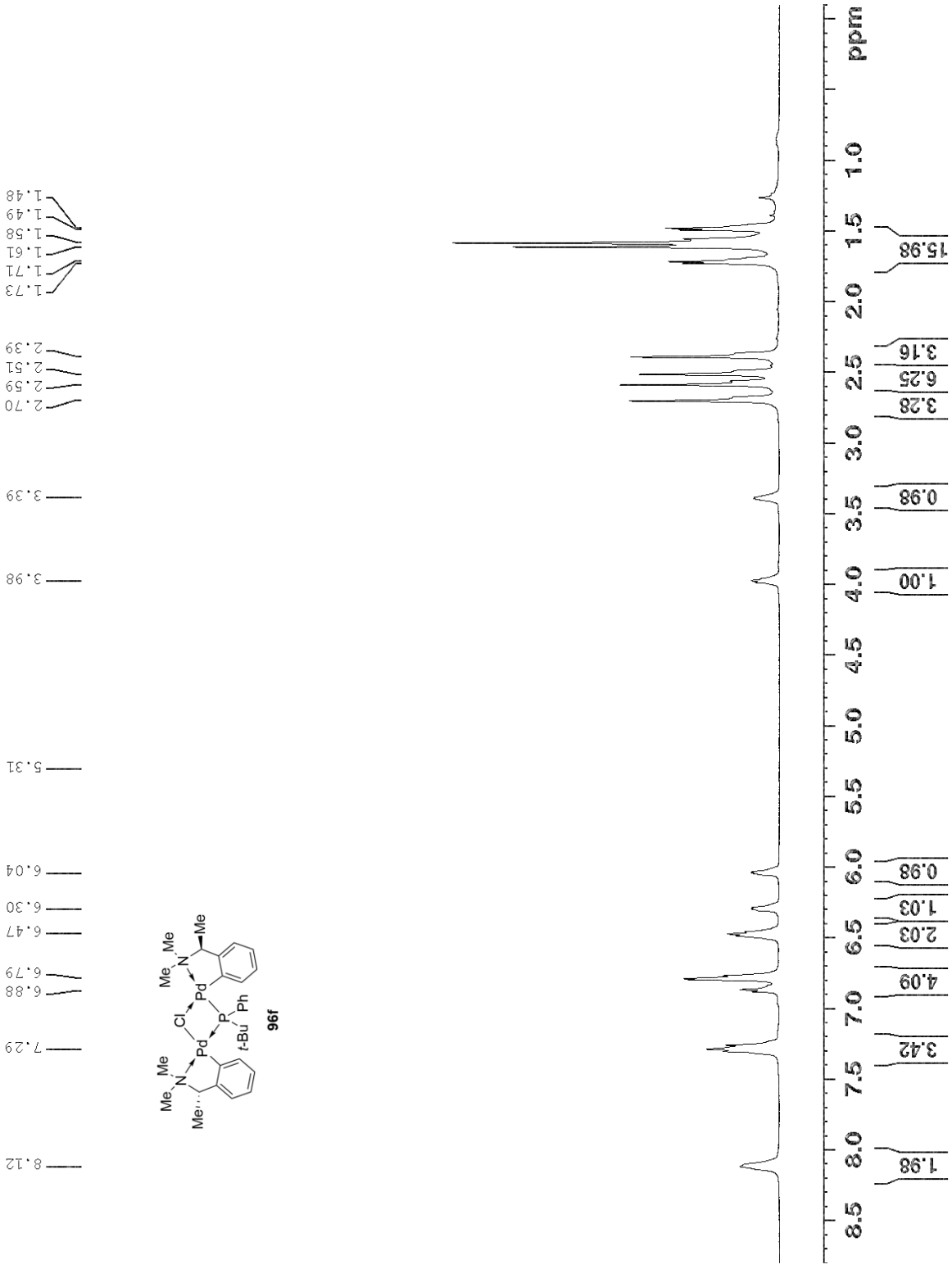


Figure 70. ^{1}H NMR spectrum of monophosphido-bridged complex **96f.**

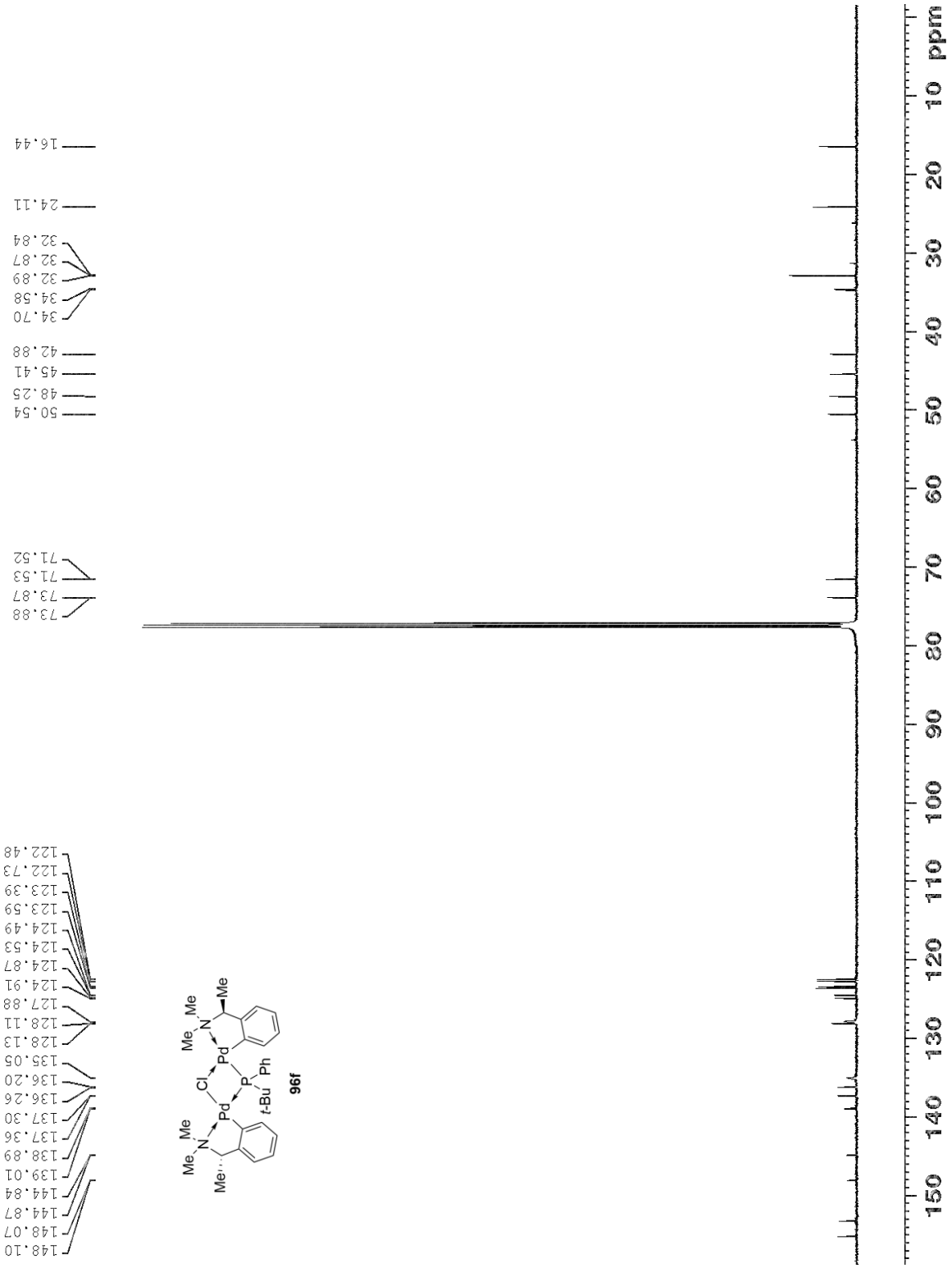


Figure 71. $^{13}C\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **96f.**

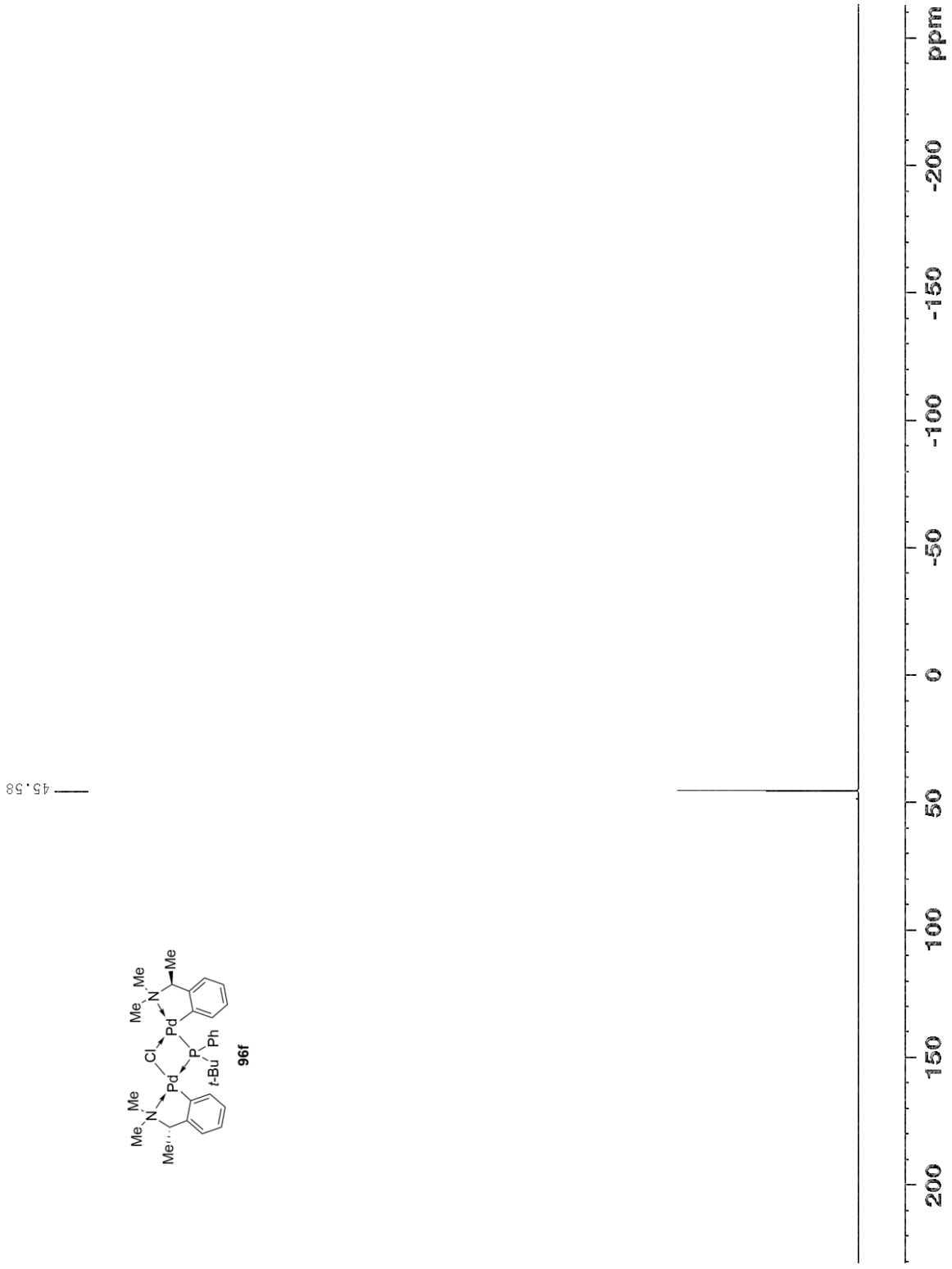


Figure 72. $^{31}P\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **96f.**

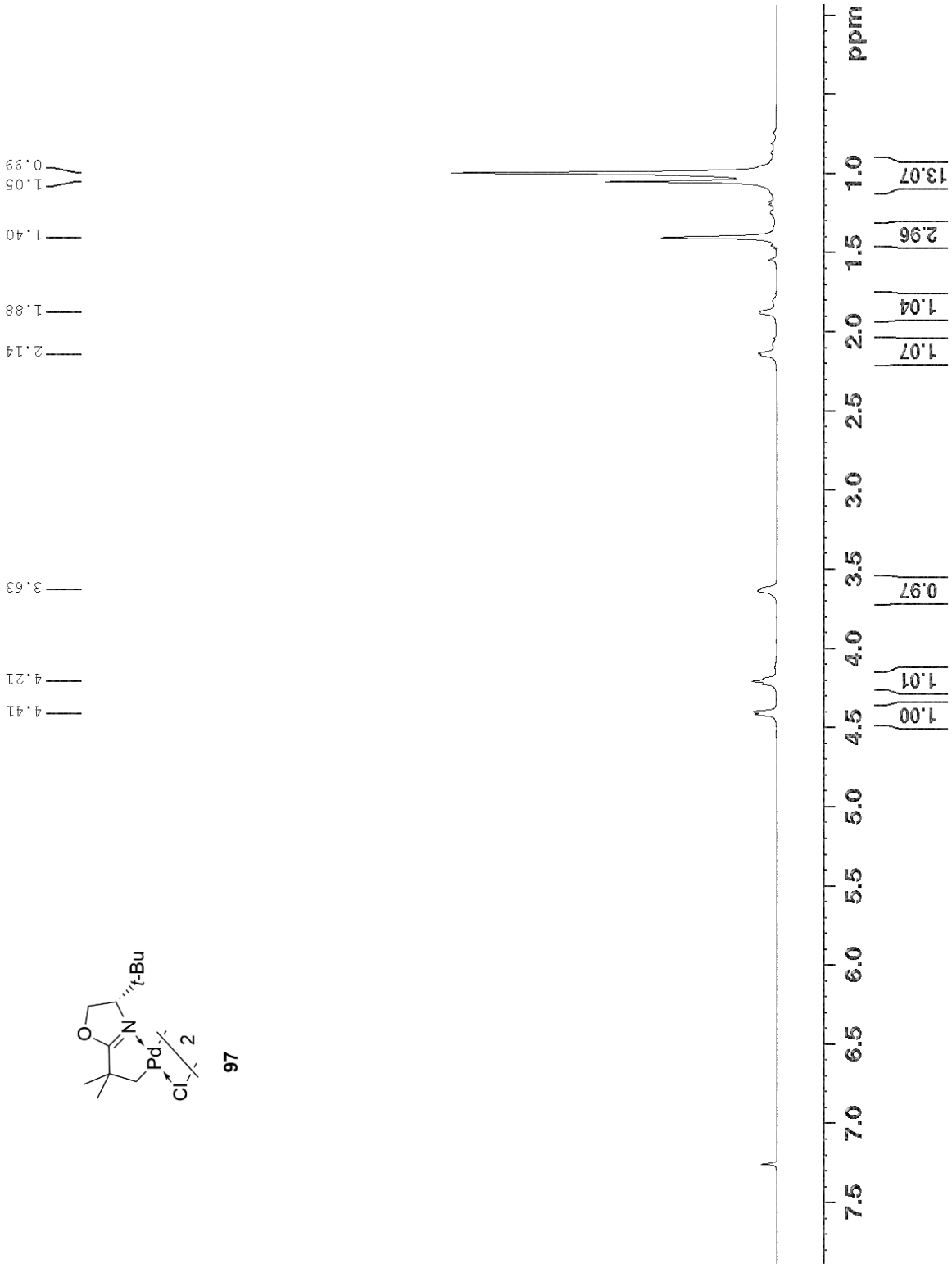


Figure 73. ^{1}H NMR spectrum of cyclopalladated complex **97.**

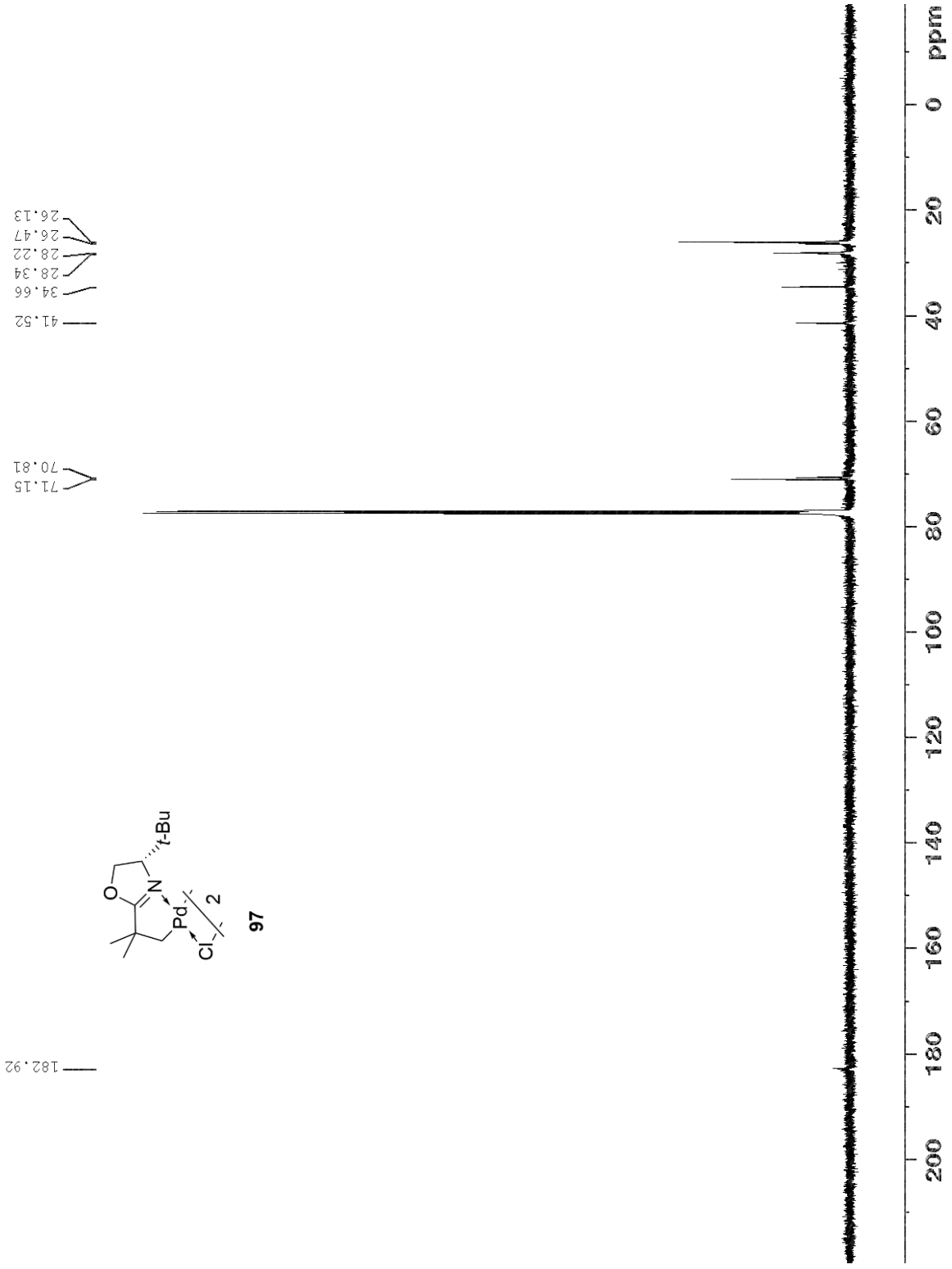


Figure 74. $^{13}C\{^{1}H\}$ NMR spectrum of cyclopalladated complex **97.**

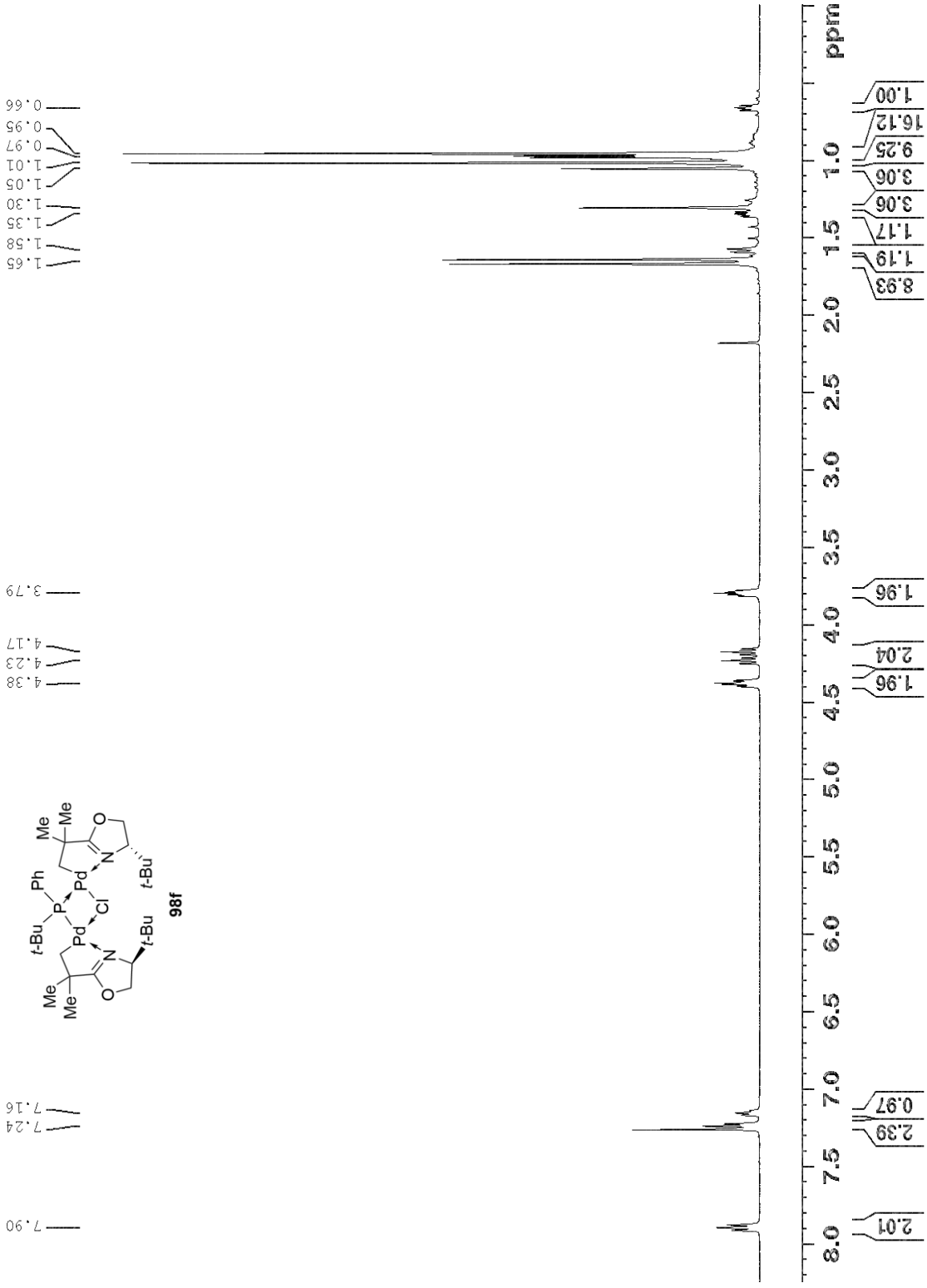


Figure 75. ^{1}H NMR spectrum of monophosphido-bridged complex **98f.**

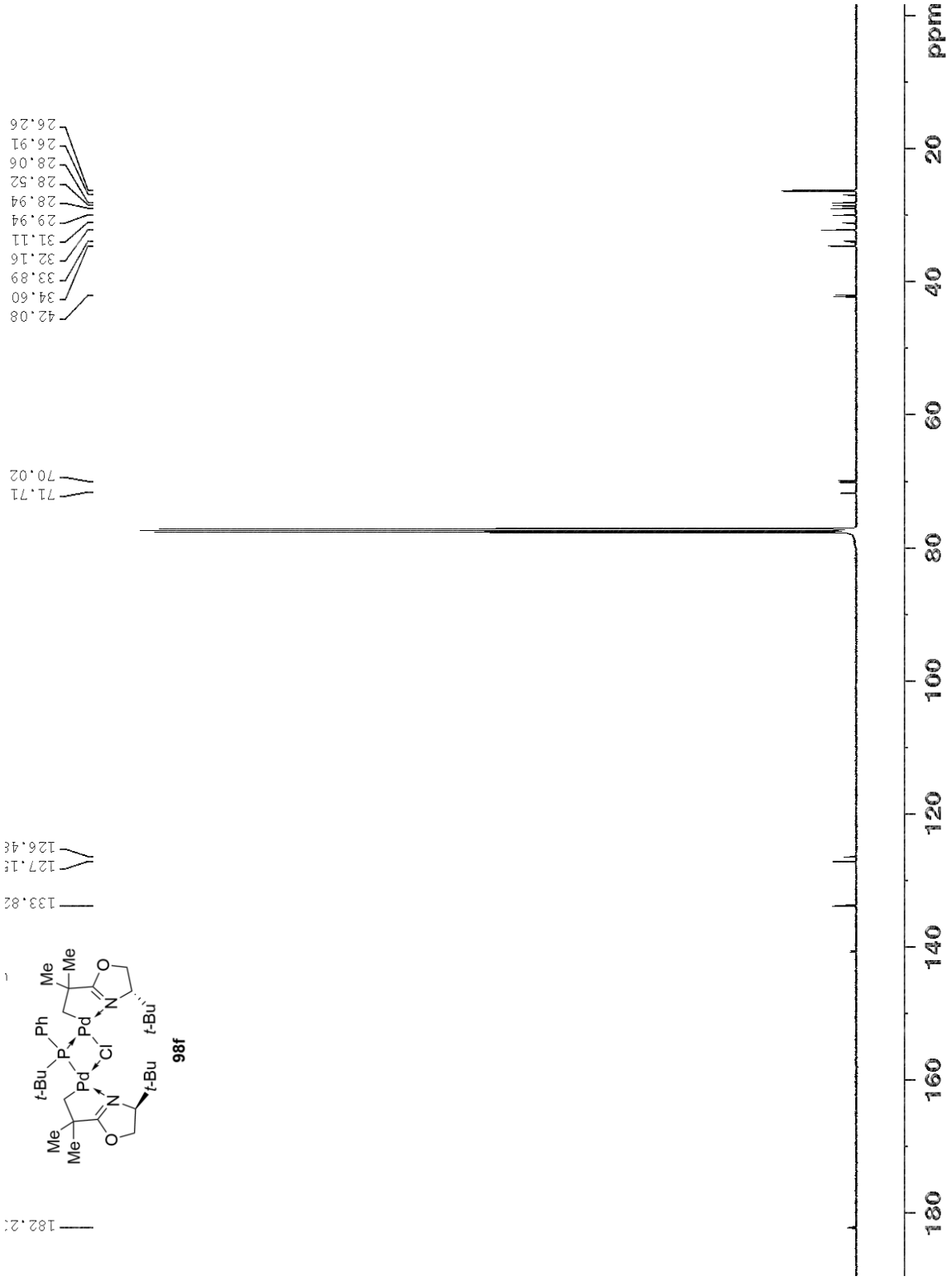


Figure 76. $^{13}C\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **98f.**

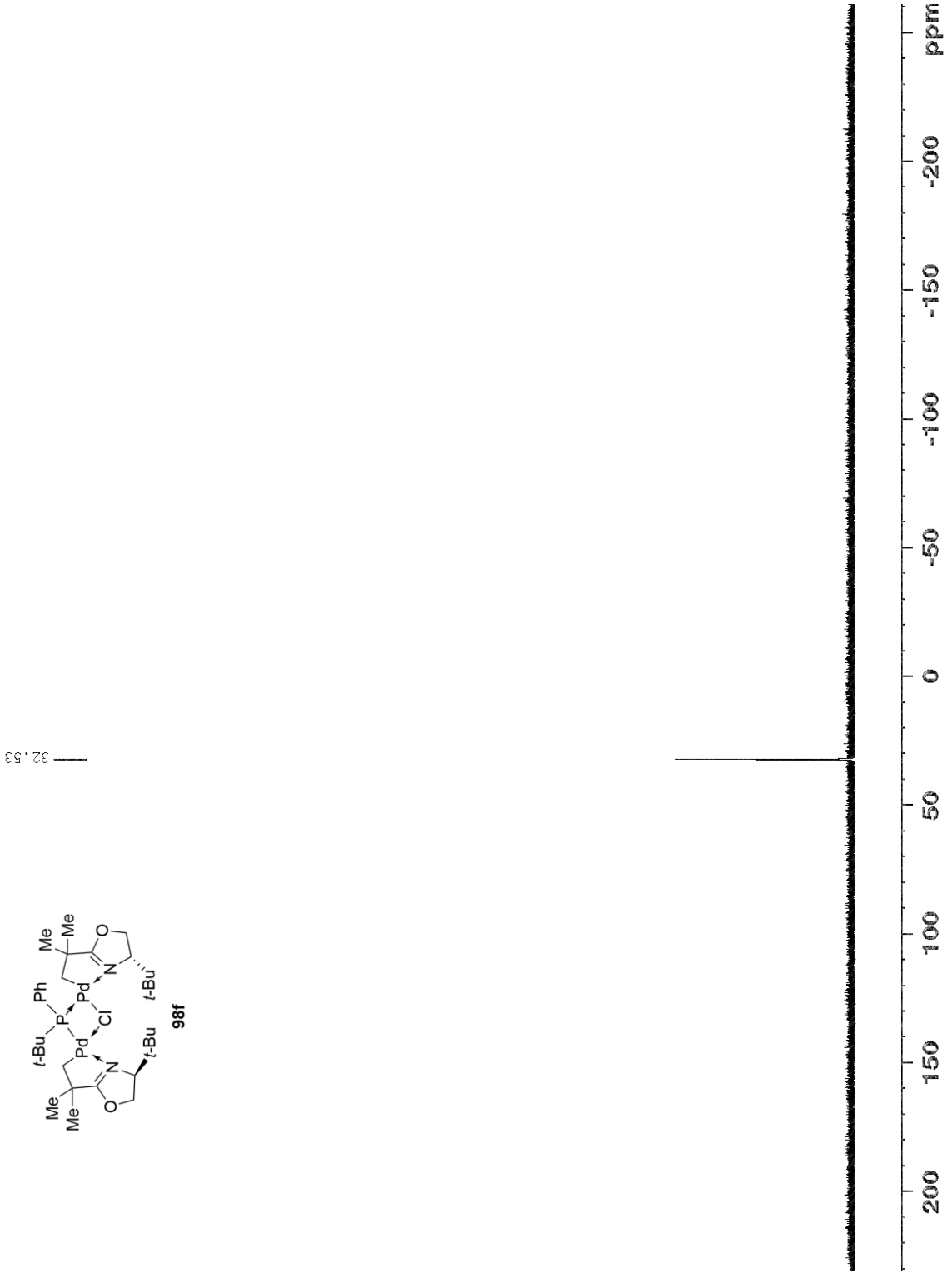


Figure 77. $^{31}P\{^{1}H\}$ NMR spectrum of monophosphido-bridged complex **98.**

Table 18. Crystal, data collection, and refinement parameters for **92d**.

Parameters	Complex **92d**
Molecular Formula	$C_{29}H_{41}ClNOPPd$
Formula Weight	592.45
Space Group	P21
Crystal System	
T, K	110
a, Å	8.3398(4)
b, Å	16.7354(8)
c, Å	20.1585(10)
α, °	90
β, °	90
γ, °	90
Volume, $Å^3$	2813.5(2)
Z	4
λ, Å	0.71073
ρ (calc), g cm^{-3}	1.399
Absorpt. Coeff., mm^{-1}	0.833
Crystal Color, Morph.	Colorless, Needle
Crystal Size, mm^3	
F(000)	1232.0
θ max	30.534
Index Ranges	
Refl. Collected	
Independ. Refl. (R_{int})	7515 (0.0334)
Observed Refl.	
Data/Restraints/Param.	
Compl. to θ	
GOF (F^2)	
R(F) [$I > 2\sigma(I)$]	
R indices (all data)	
Larg. Diff. Peak, Hole	

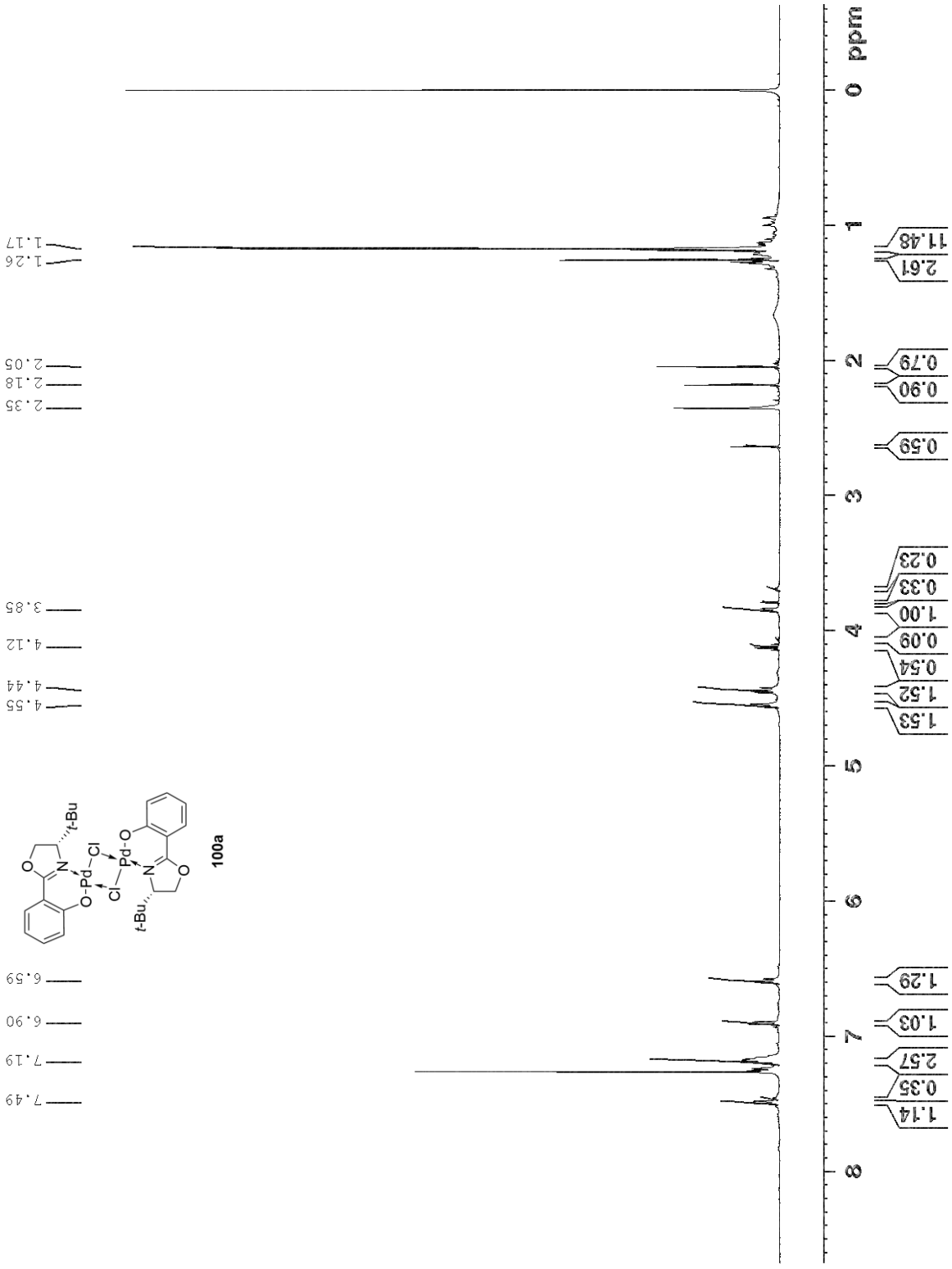


Figure 78. ^{1}H NMR spectrum of di-μ-chloro complex **100a**.

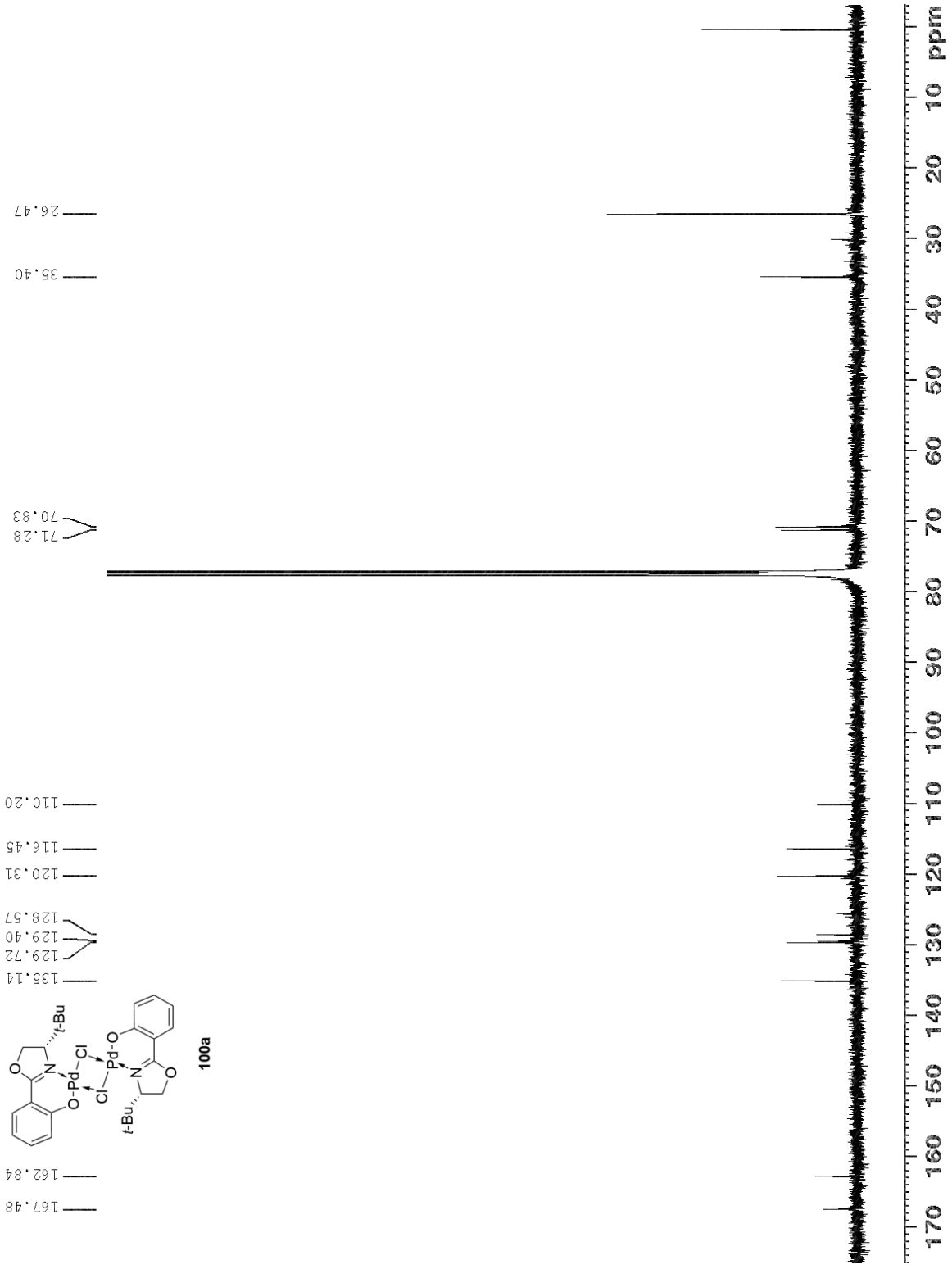


Figure 79. $^{13}C\{^{1}H\}$ NMR spectrum of di-μ-chloro complex **100a**.

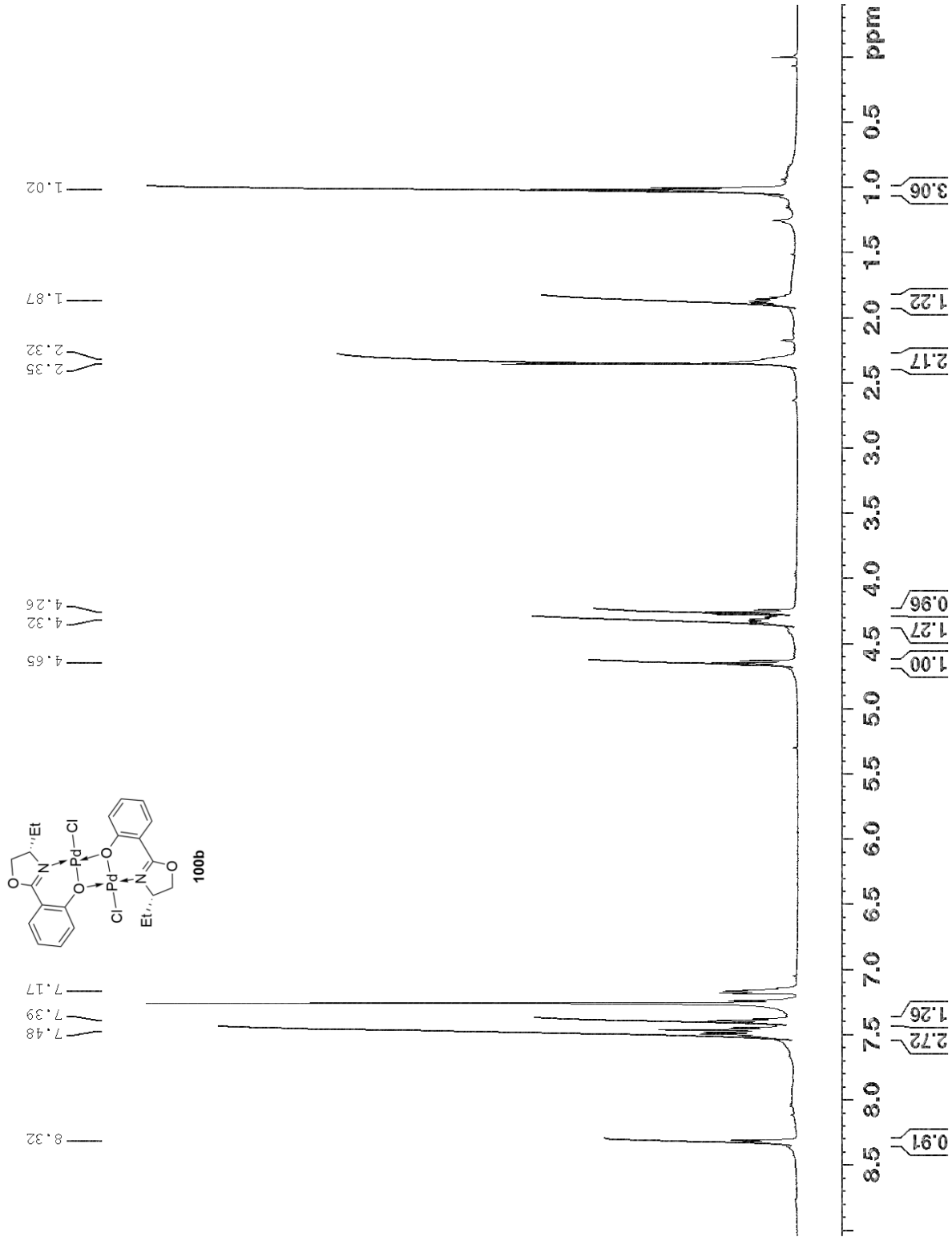


Figure 80. ^{1}H NMR spectrum of di-μ-oxo complex **100b**.

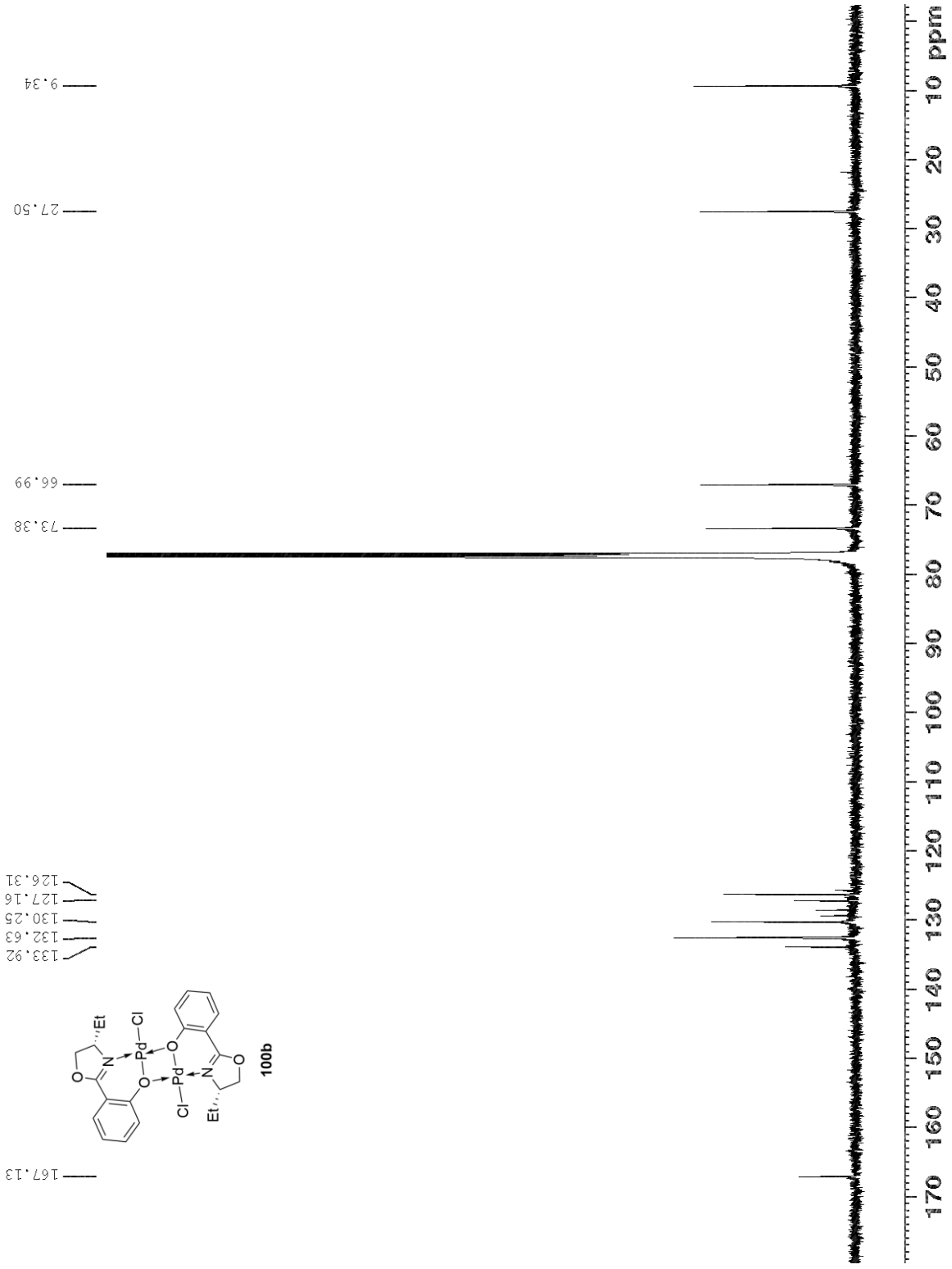


Figure 81. $^{13}C\{^{1}H\}$ NMR spectrum of di-μ-oxo complex **100b**.

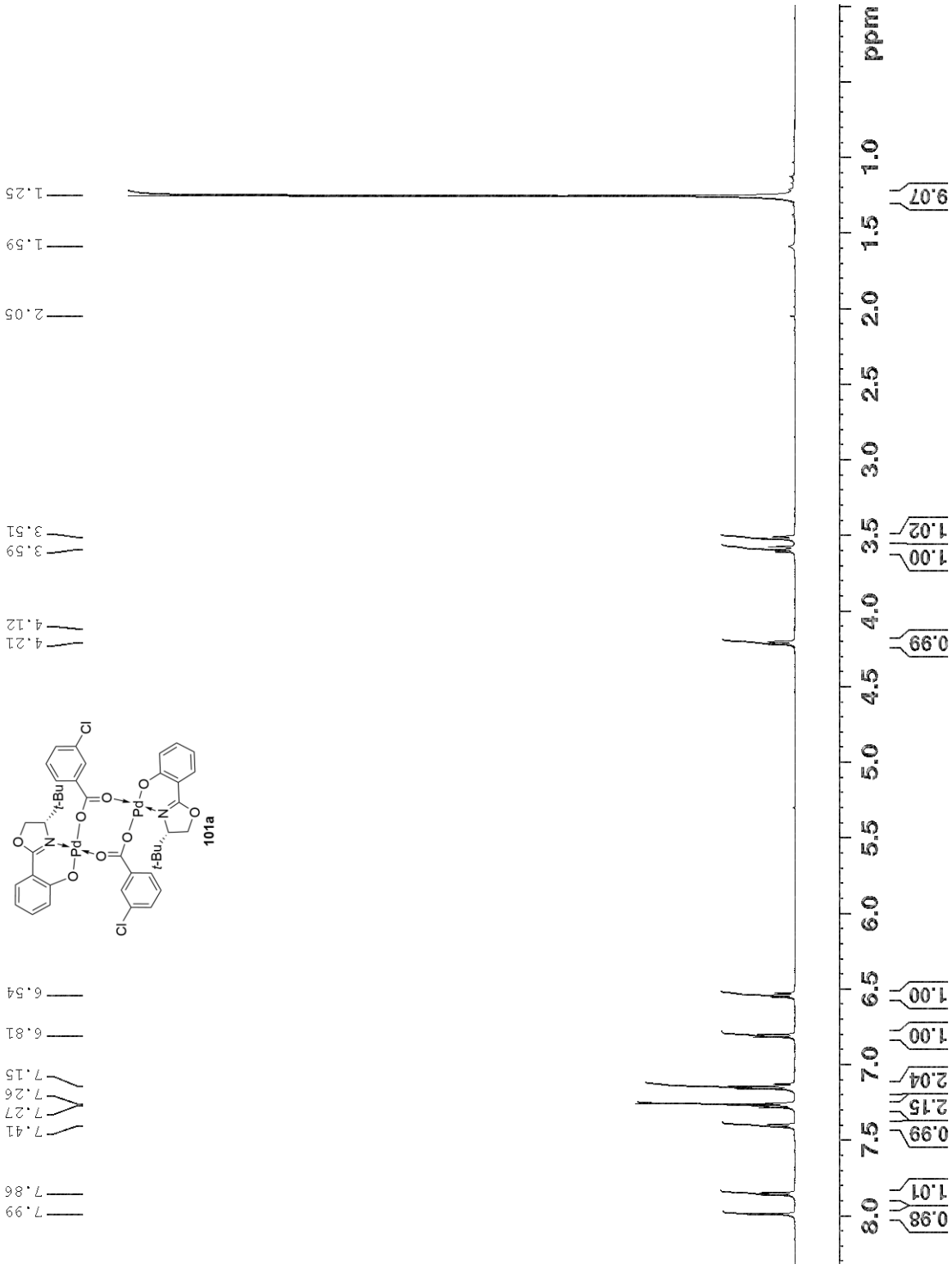


Figure 82. ^{1}H NMR spectrum of di-μ-3-chlorobenzoato complex **101a**.

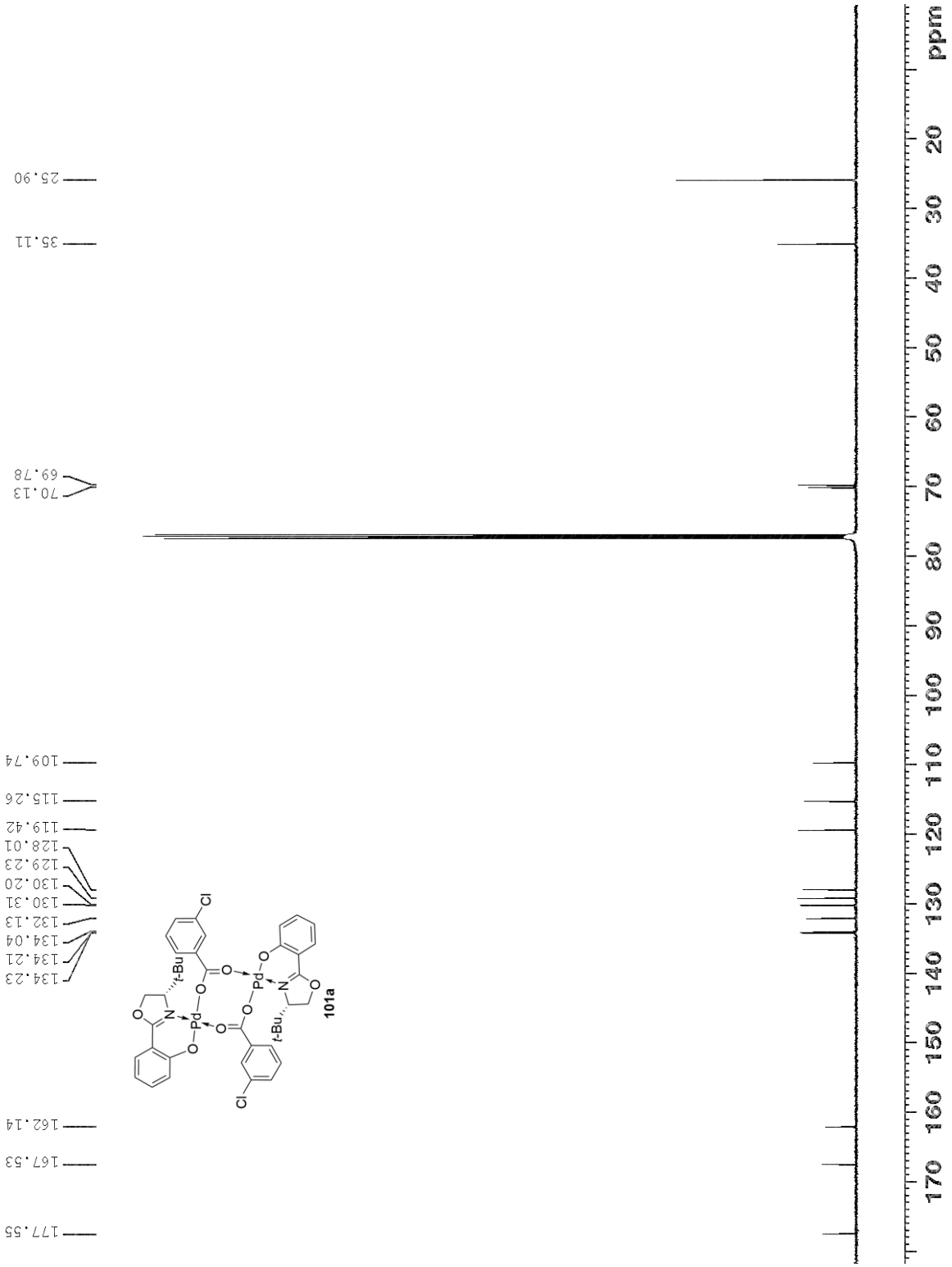


Figure 83. $^{13}C\{^{1}H\}$ NMR spectrum of di-μ-3-chlorobenzoato complex **101a**.

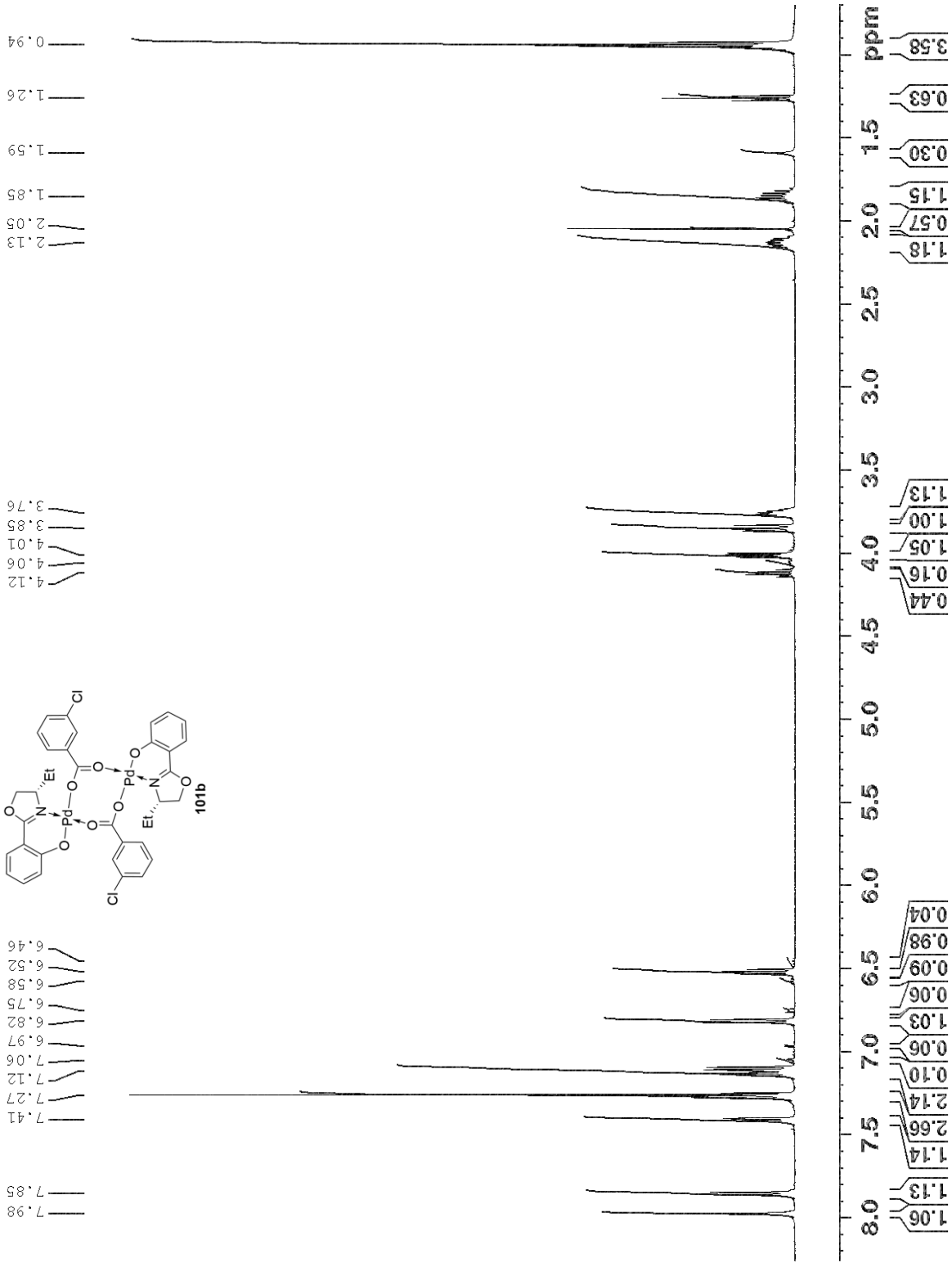


Figure 84. ^{1}H NMR spectrum of di-μ-3-chlorobenzoato complex **101b**.

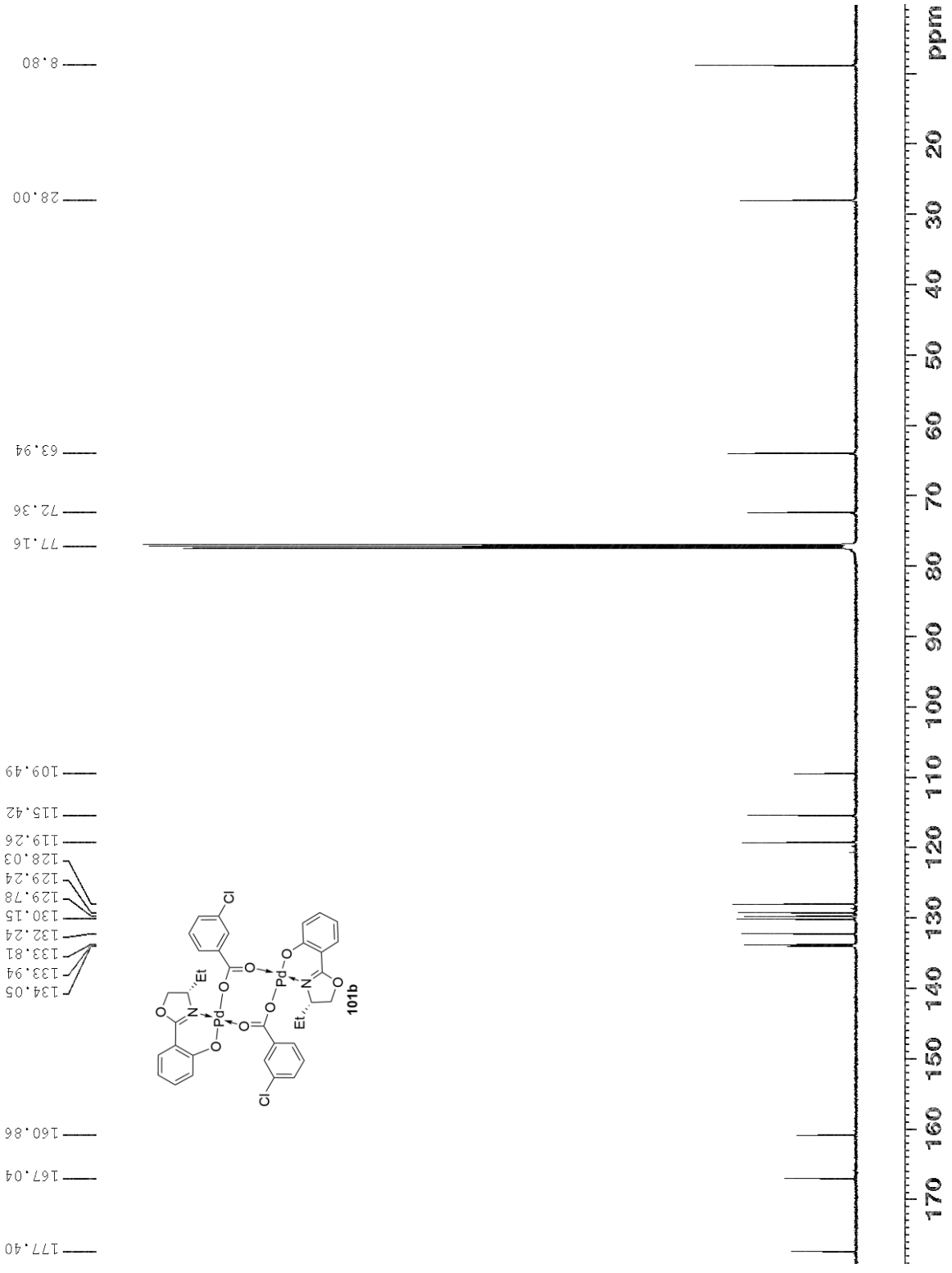


Figure 85. $^{13}C\{^{1}H\}$ NMR spectrum of di-μ-3-chlorobenzoato complex **101b**.

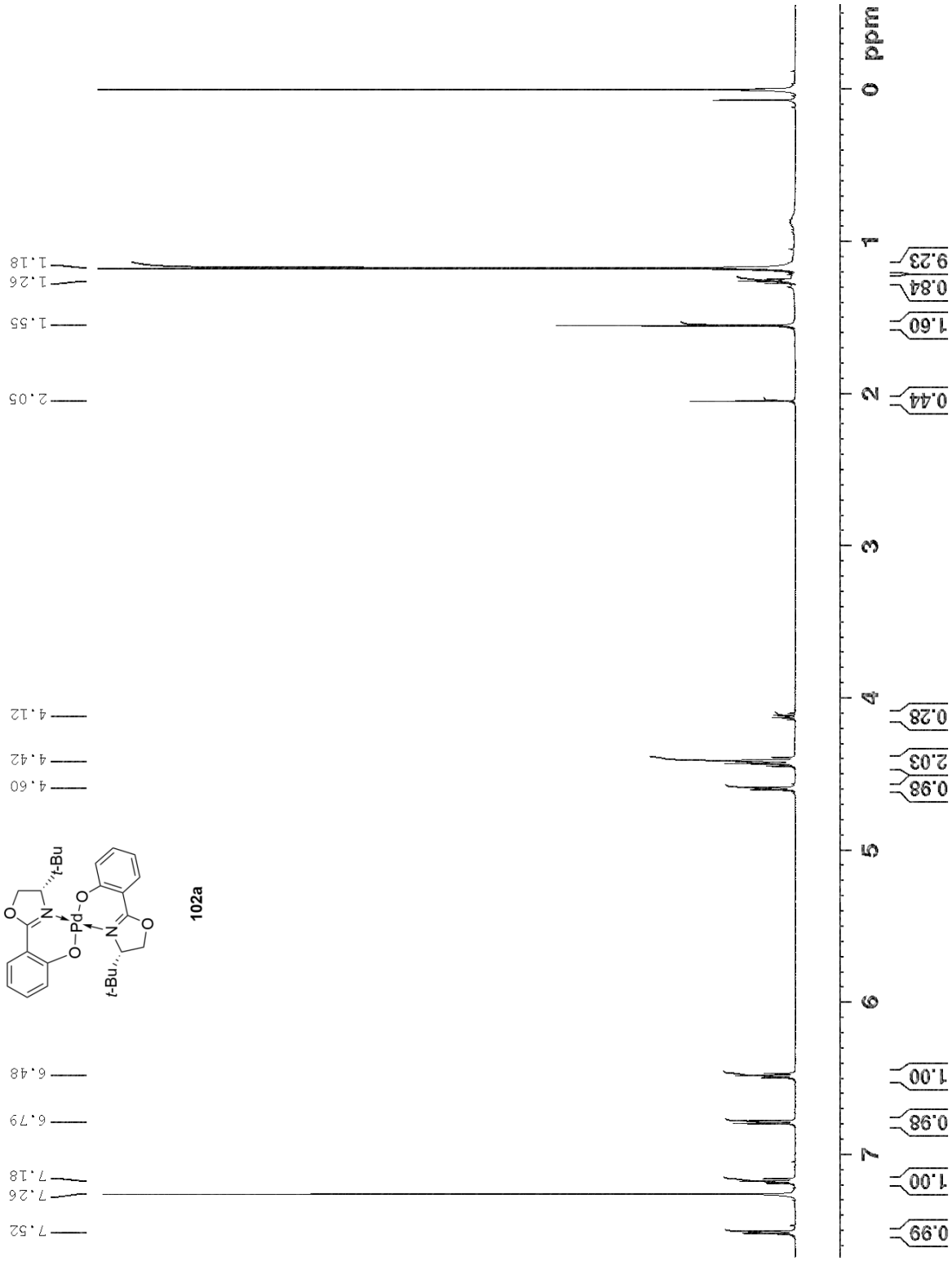


Figure 86. ^{1}H NMR spectrum of bis($\kappa^{2}N,O$)Pd complex **102a**.

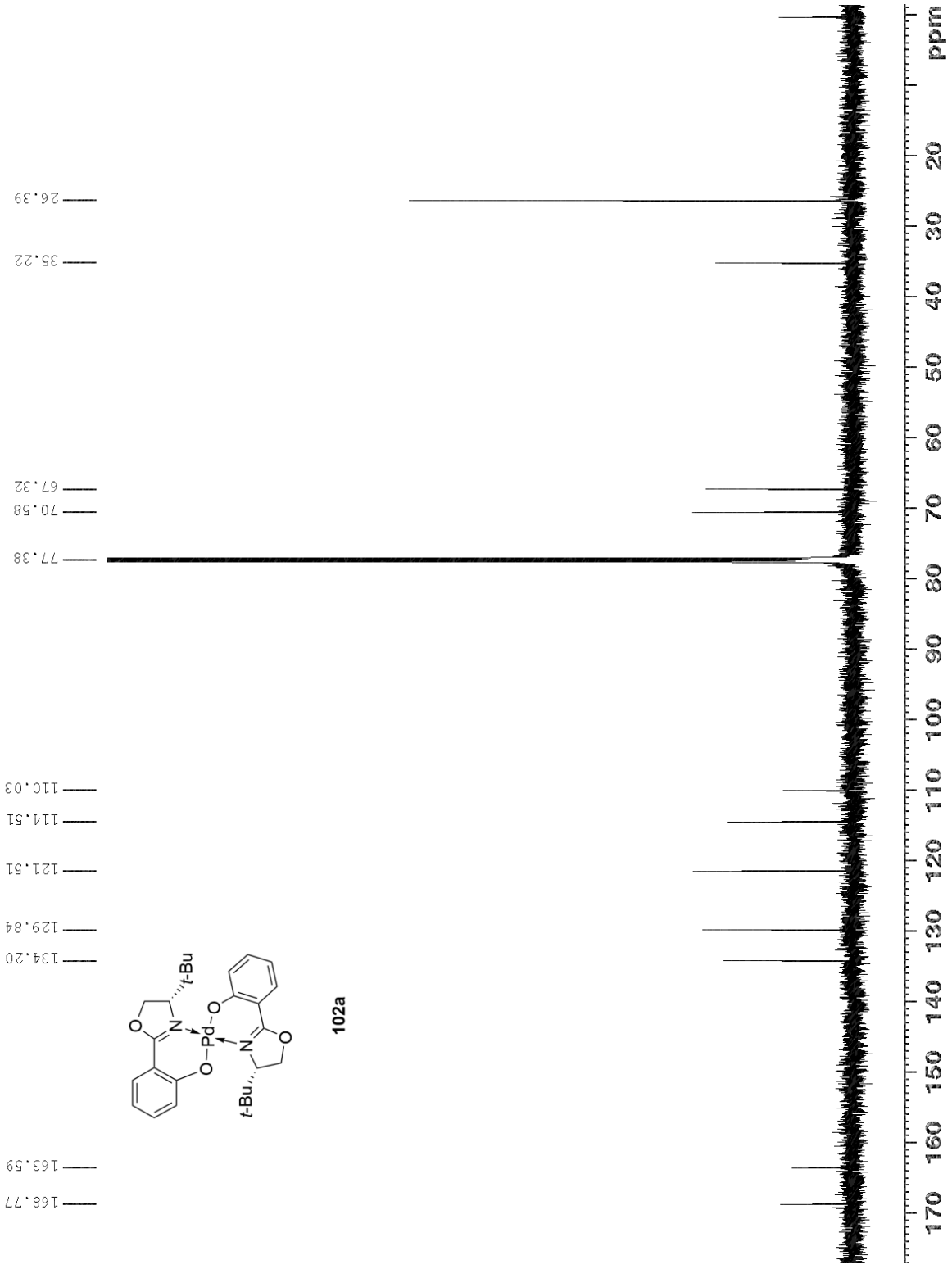


Figure 87. $^{13}C\{^{1}H\}$ NMR spectrum of bis(κ^2N,O)Pd complex **102a**.

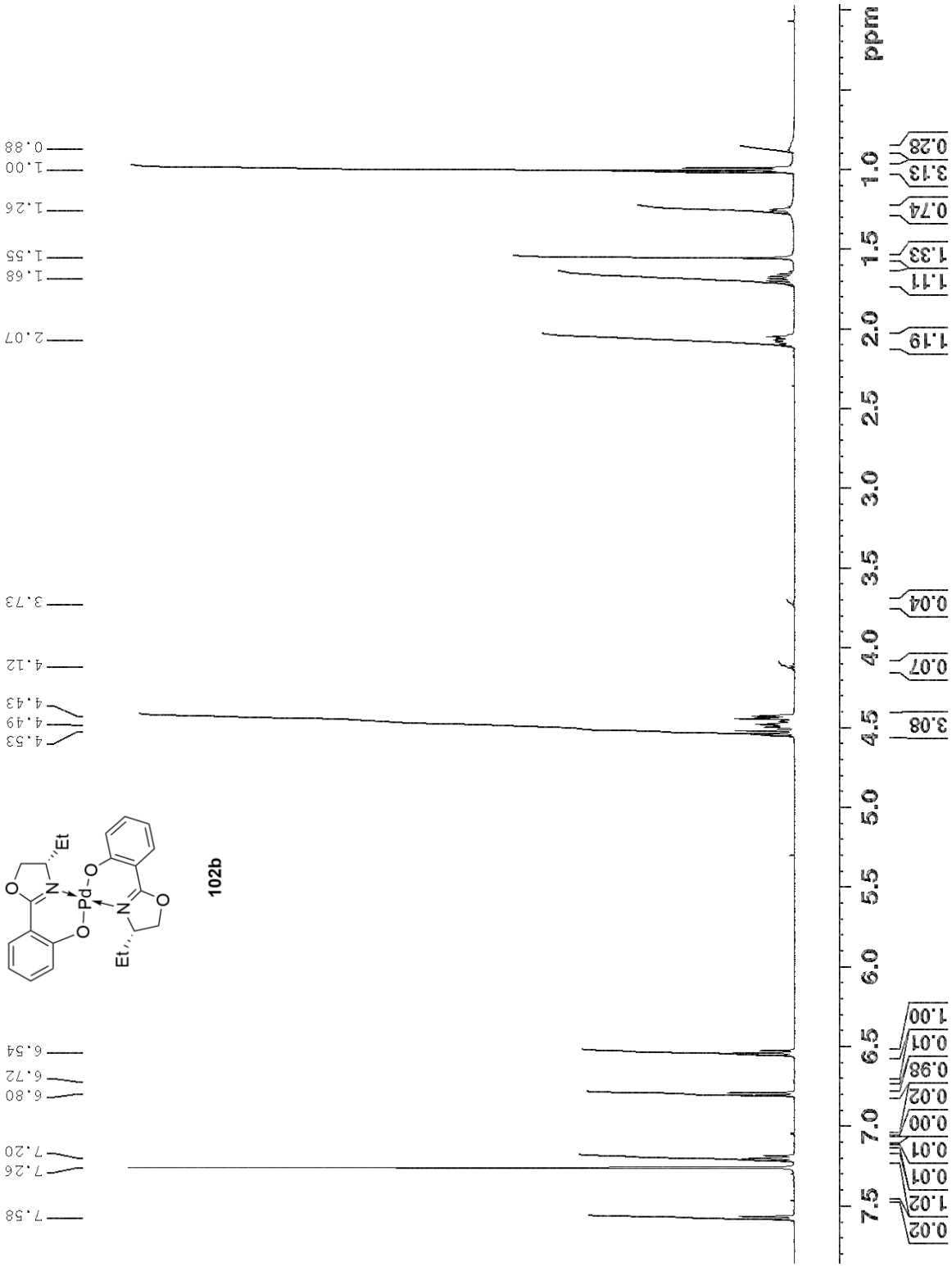


Figure 88. ^{1}H NMR spectrum of bis($\kappa^{2}N,O$)Pd complex **102b**.

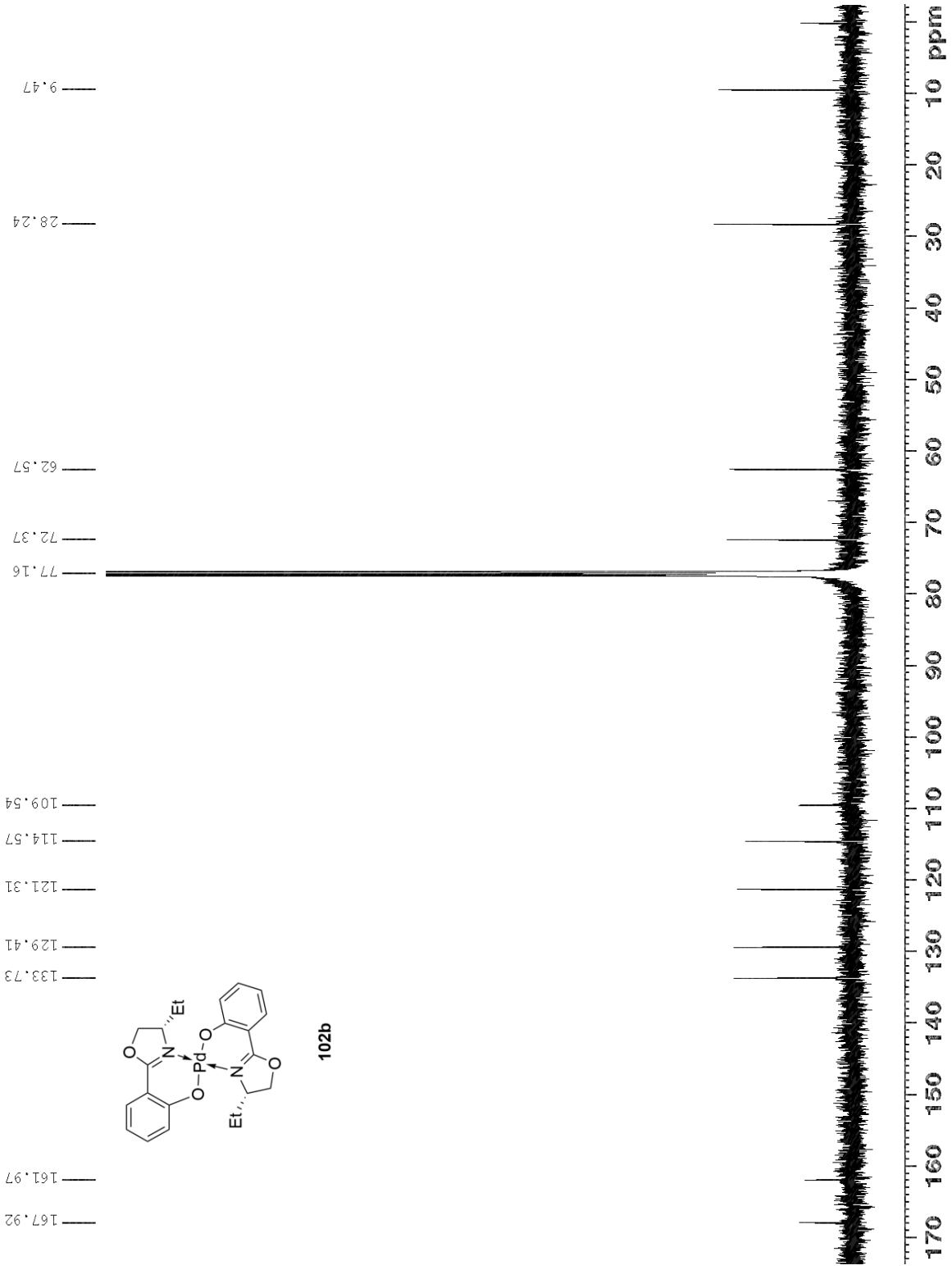


Figure 89. $^{13}C\{^{1}H\}$ NMR spectrum of bis(κ^2N,O)Pd complex **102b**.

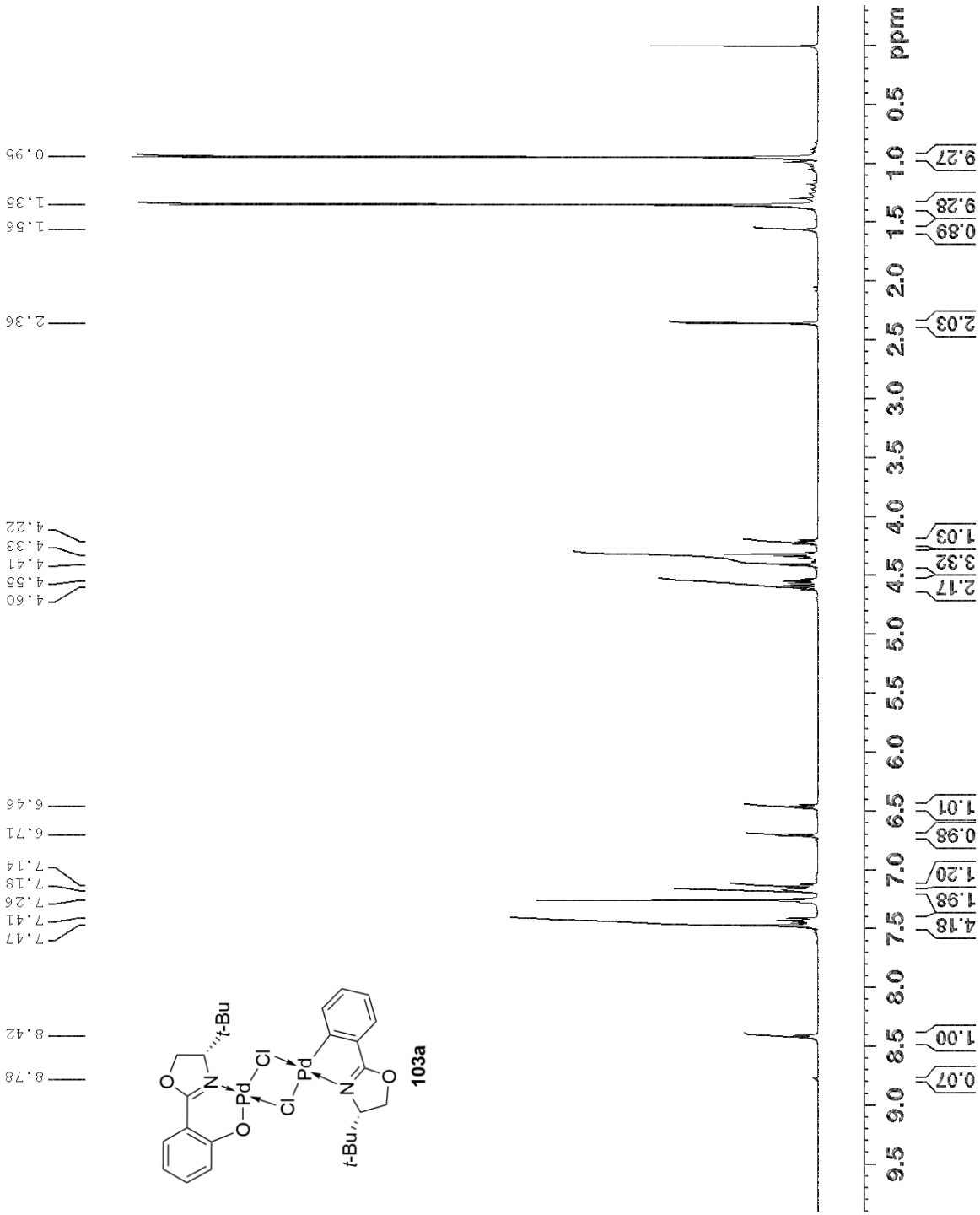


Figure 90. ^{1}H NMR spectrum of dimeric mono-insertion complex **103a**

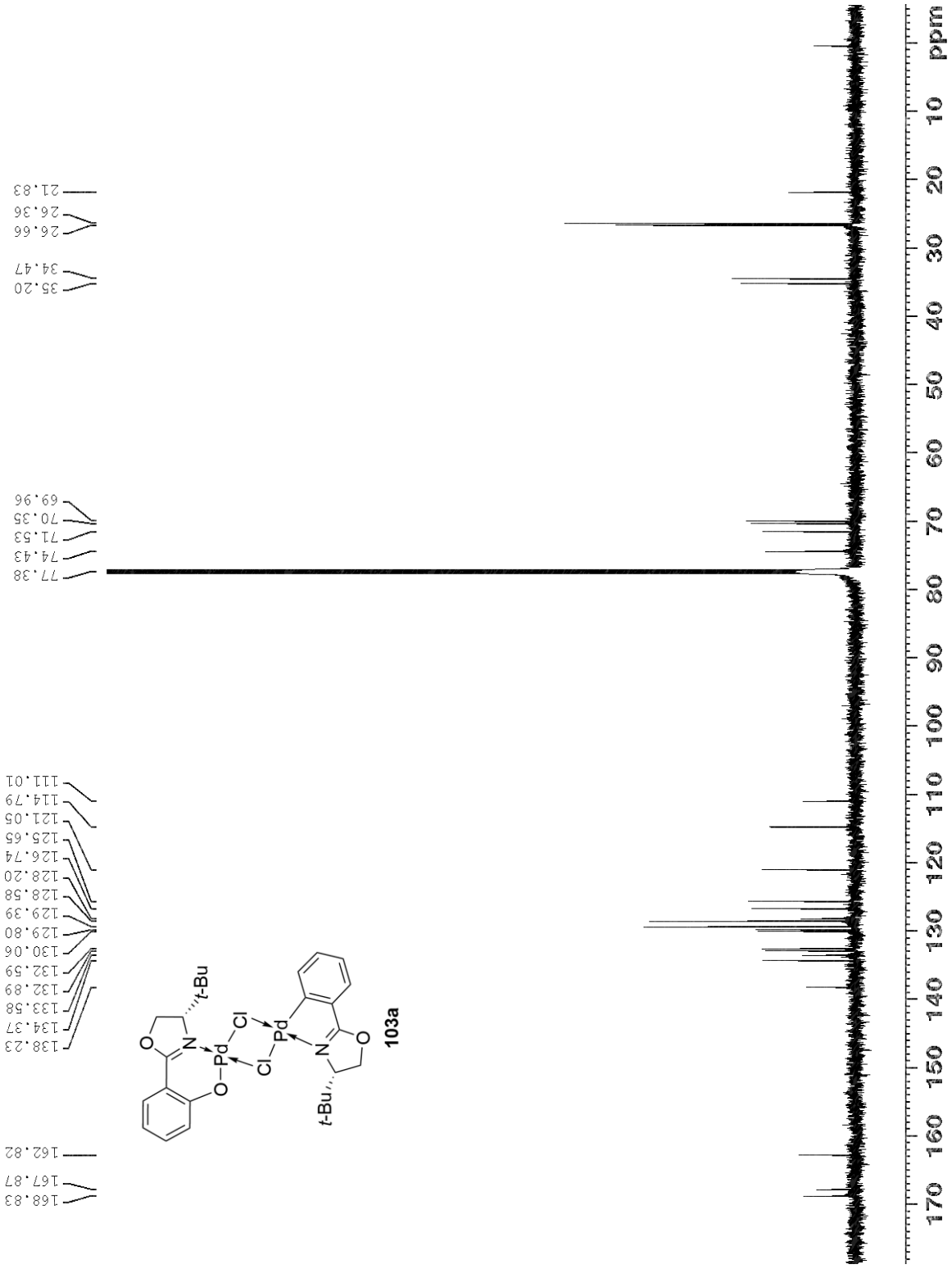


Figure 91. $^{13}C\{^{1}H\}$ NMR spectrum of dimeric mono-insertion complex **103a**

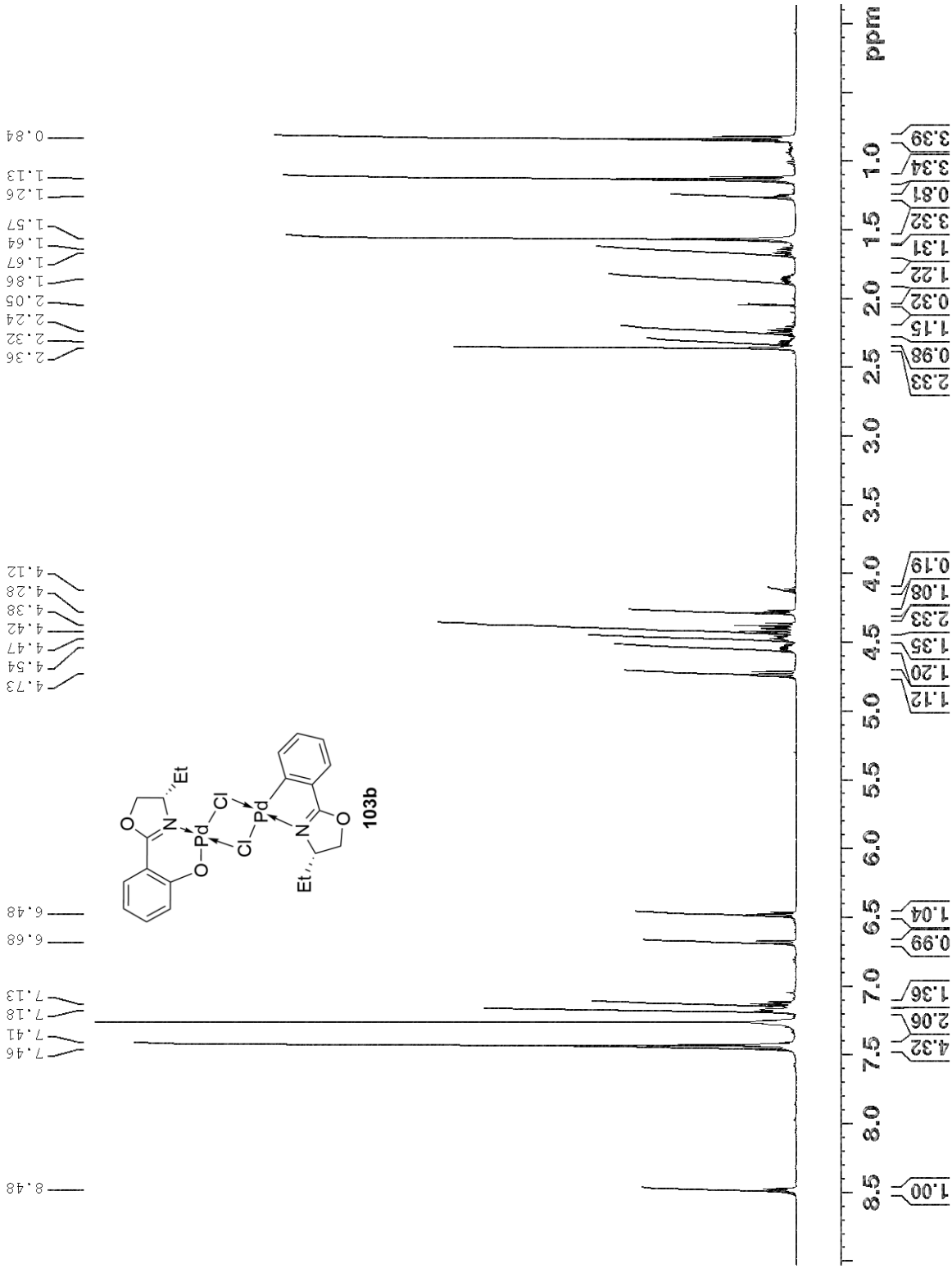


Figure 92. ^{1}H NMR spectrum of dimeric mono-insertion complex **103b**

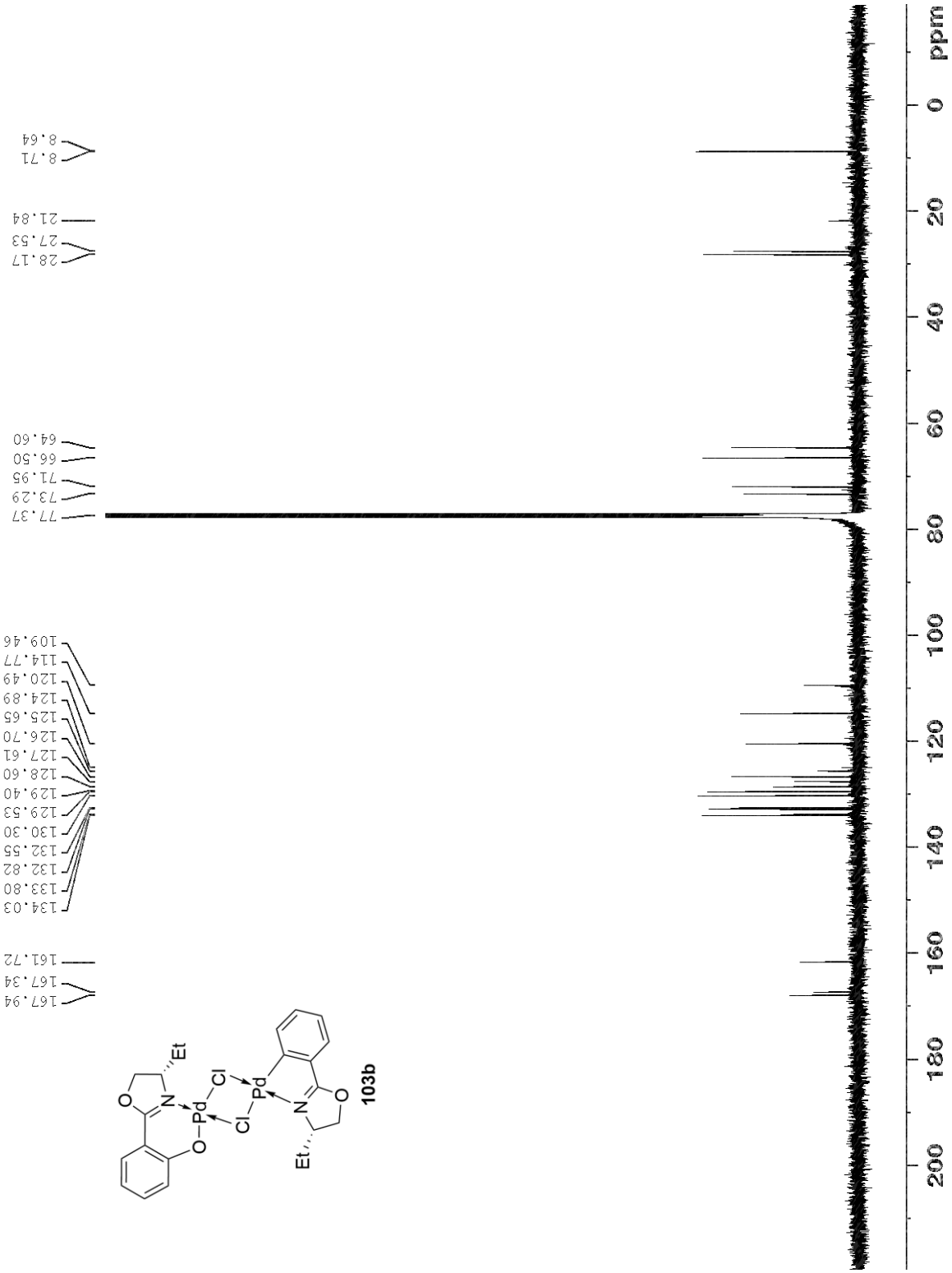


Figure 93. $^{13}C\{^{1}H\}$ NMR spectrum of dimeric mono-insertion complex **103b**

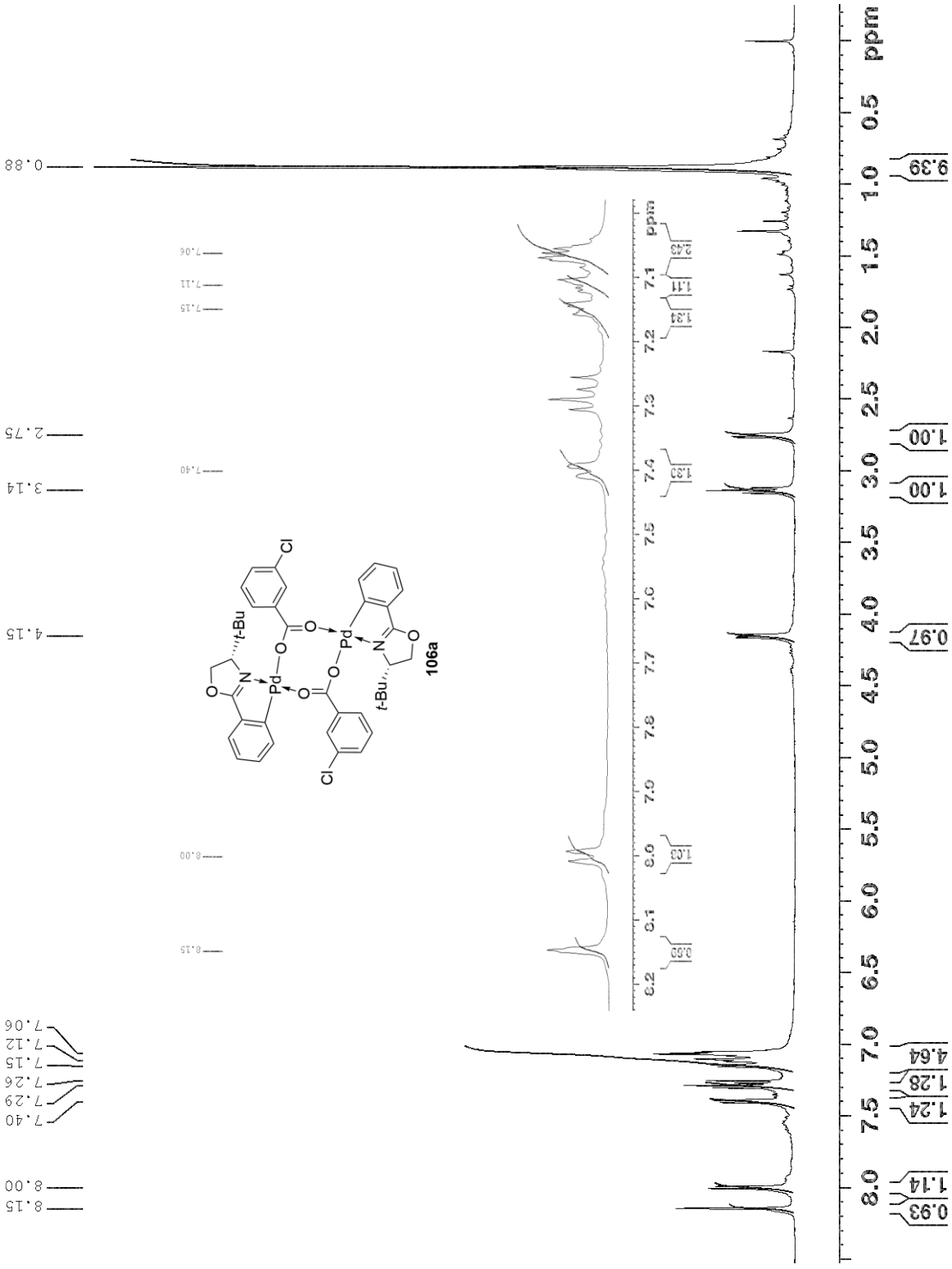


Figure 94. ^{1}H NMR spectrum of di-μ-chlorobenzoato complex **106a**.

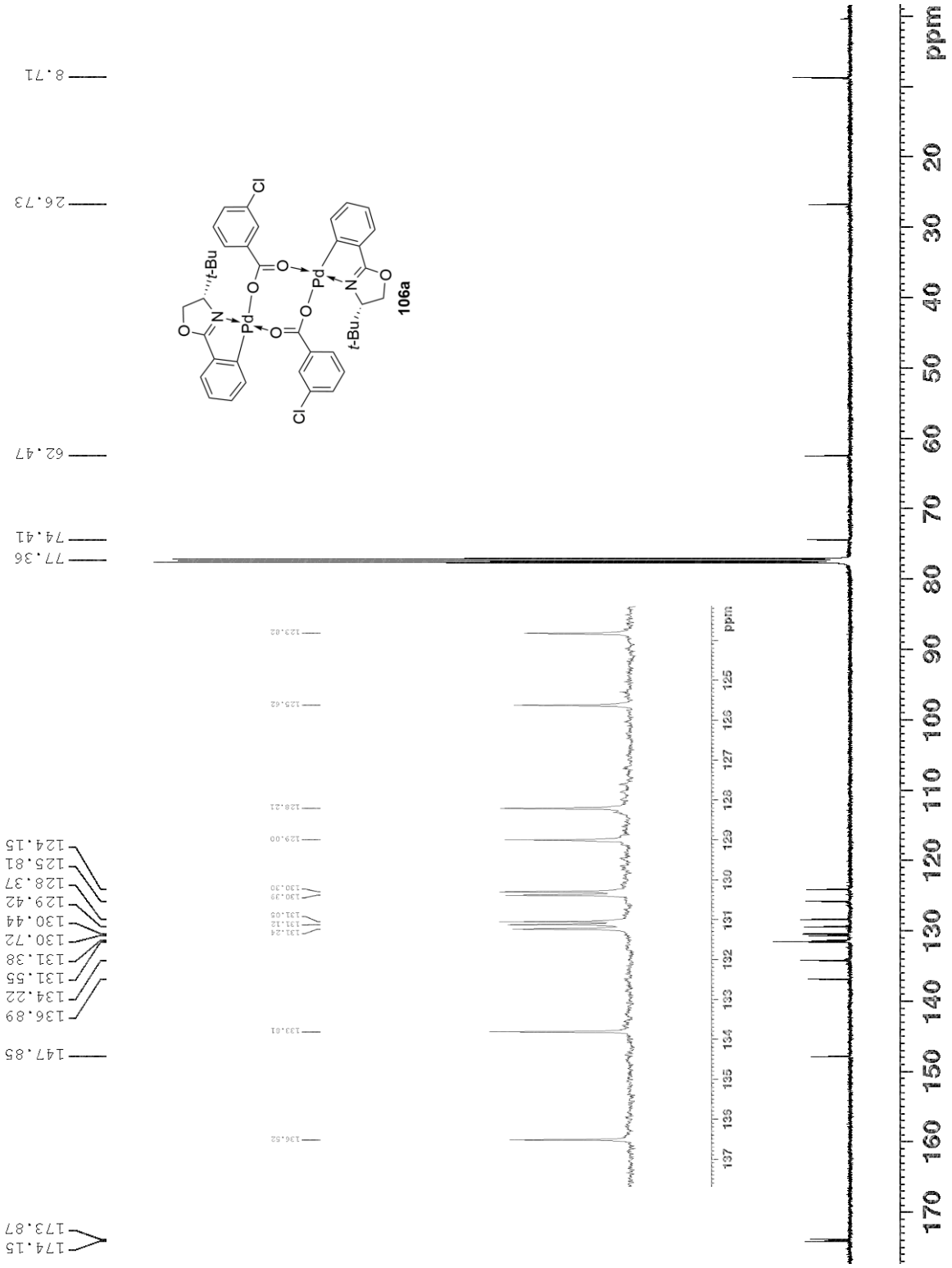


Figure 95. $^{13}C\{^{1}H\}$ NMR spectrum of di-μ-chlorobenzoato complex **106a**.

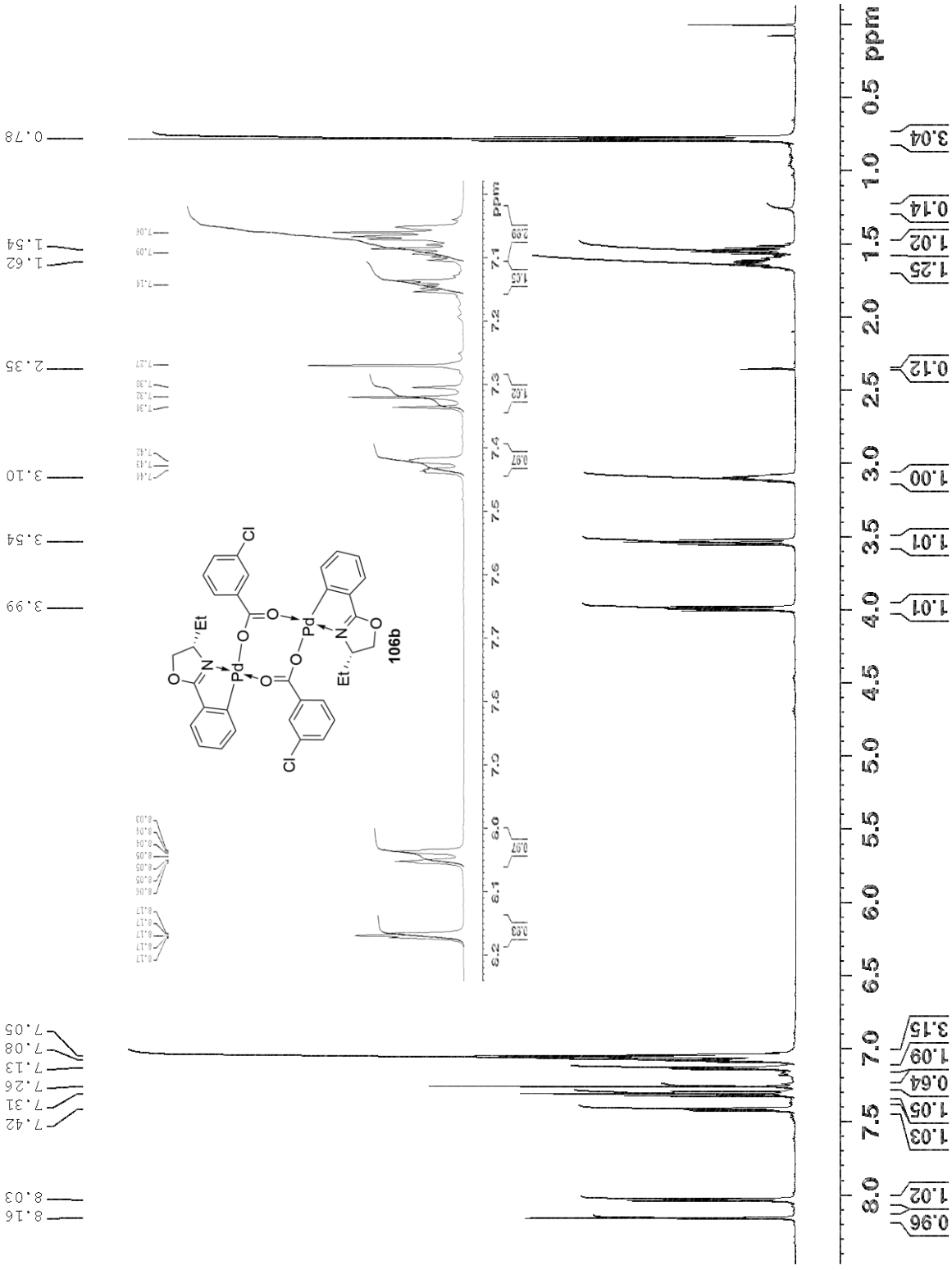


Figure 96. ^{1}H NMR spectrum of di-μ-chlorobenzoato complex **106b**.

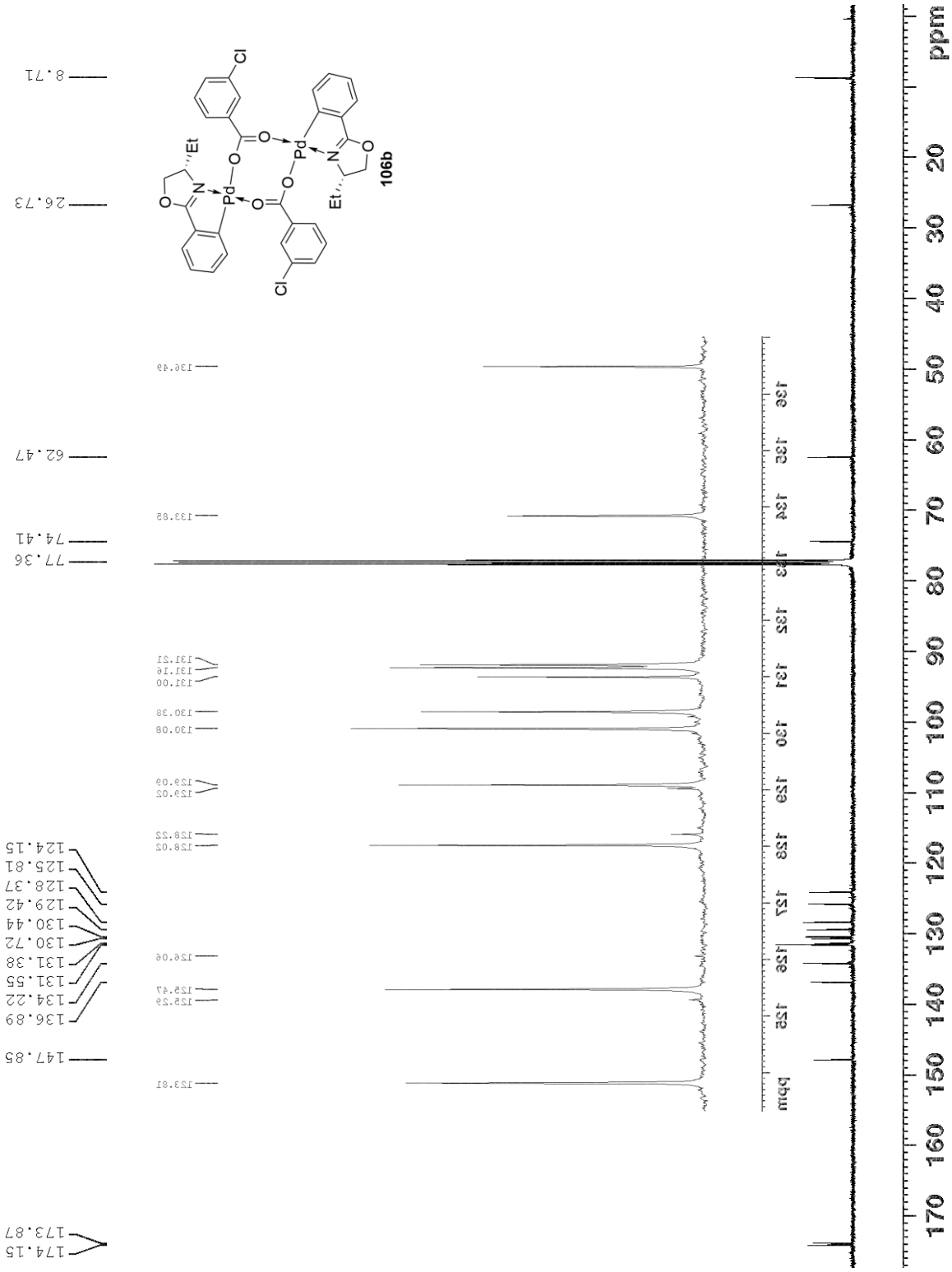


Figure 97. $^{13}C\{^{1}H\}$ NMR spectrum of di-μ-chlorobenzoato complex **106b**.

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